

SECTION 4

CLIMATE CHANGE

**A GLOBAL
PROBLEM WITH
LOCAL IMPACTS**

Downtown Bellingham, WA from the Lummi Nation
Photo: Nick Pinkham

SECTION 4

PHYSICAL EVIDENCE OF CLIMATE CHANGE

Air Temperature
Freshwater Delivery
Sea Water Temperature
Ocean Acidification
Dissolved Oxygen
Sea Level Rise

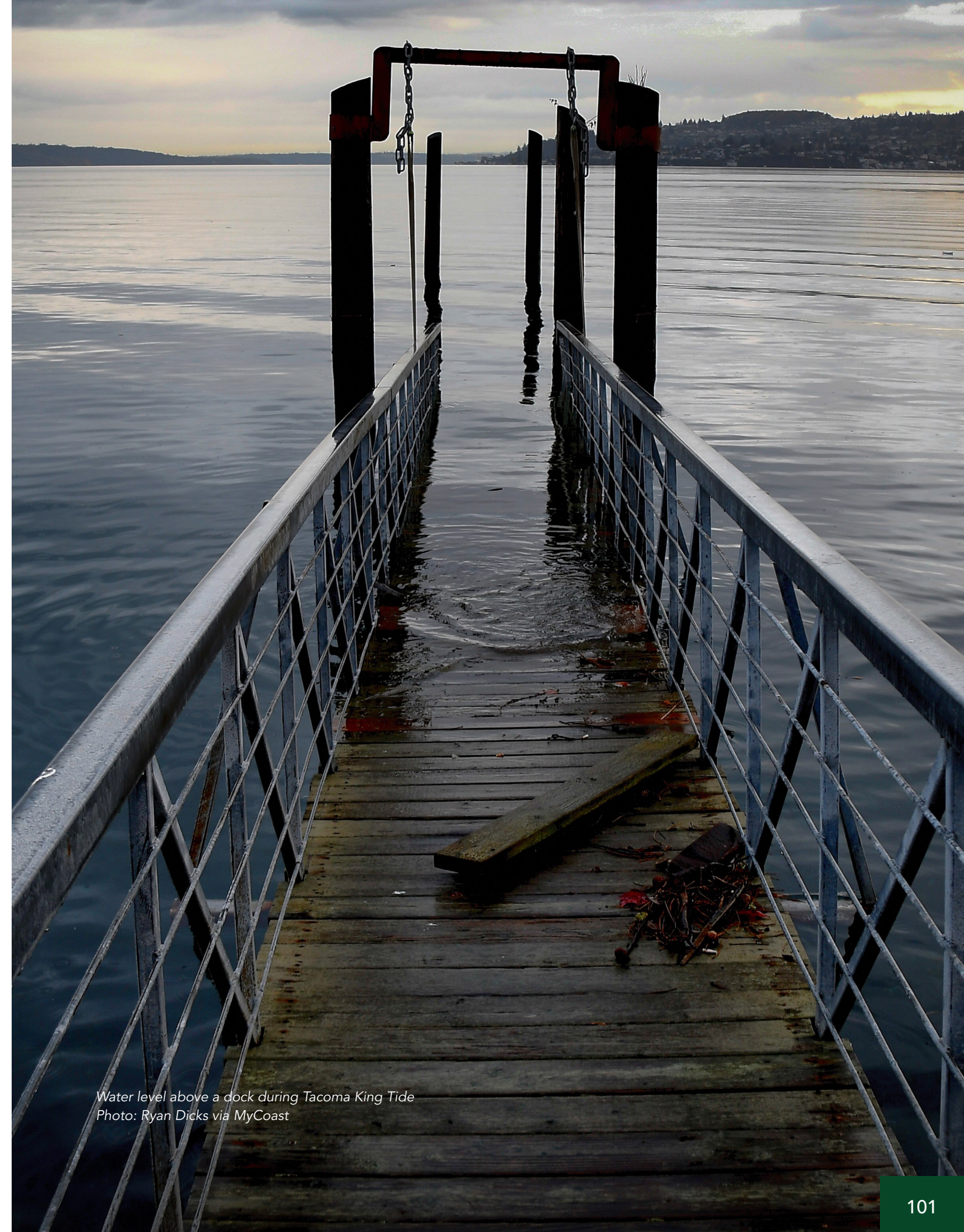
ECOLOGICAL EVIDENCE OF CLIMATE CHANGE

Phytoplankton
Kelp
Coastal Wetlands
Salmon
Marine Birds

SUMMARY OF CLIMATE CHANGE IN THE SALISH SEA

VIGNETTES

12: The Blob
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Water level above a dock during Tacoma King Tide
Photo: Ryan Dicks via MyCoast

Twenty-five years ago when *The Shared Waters Report* was written, scientists were beginning to identify concerns associated with climate change in the Salish Sea. Today, scientists more fully recognize, catalog, and quantify the ongoing impacts of climate change and are working to predict what further effects it might trigger in the coming decades.

Observed changes to the Salish Sea ecosystem include documented long-term trends across several critical atmospheric, hydrologic, biologic, and geophysical parameters, and also include more abrupt and anomalous conditions like the 2014-2016 marine heat wave known as “the Blob.” Modeling studies that incorporate climate projections and concomitant changes to physical processes supplement those empirical observations to provide additional indications of regional changes that have already occurred and that are probable with continued global climate change.

Climate change modeling and projections are understandably uncertain, and the resulting responses from biota are even more uncertain because multiple impacts may change organism populations and communities in nonlinear ways. However, as recognized by numerous researchers and studies cited in this report, predictions about ecosystem impacts will continue to be vital and will benefit from more transboundary cooperation, additional carefully designed small-scale experiments, and development of truly integrated models where large-scale simulations are possible and likely to generate new insights leading to sustainable solutions.

Climate vs. Climate Change

Climate is the slowly varying aspects of the atmosphere-hydrosphere-land system. Climate is determined by the long-term pattern—averages, variability, and extremes—of temperatures, precipitation, and winds at a location and can be variable even over short distances. Climate descriptions can refer to various spatial scales (local, regional, or global) and temporal scales (decades, years, seasons, months, or specific dates). Climate change, on the other hand, is any systematic change in the long-term statistics of climate elements from one system state to another, where the new state is sustained (over several decades or longer). Climate change may be due to natural external forcings, such as changes in solar emission or slow changes in the earth’s orbital elements, natural internal processes of the climate system, or anthropogenic forcing (American Meteorological Society n.d.). Vernacularly, climate change refers specifically to the rise in global temperatures and associated physical and chemical forcings from the mid-20th century to present that result from anthropogenic causes, and that is the sense it is used herein.

PHYSICAL EVIDENCE OF CLIMATE CHANGE

Increasing greenhouse gas emissions, and the resulting increases in atmospheric concentrations of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) are driving changes to the earth system, referred to as climate change. The impacts of climate change are largely driven by physical forcing (changes and drivers of change in physical processes), the first and foremost of which is global temperature of the air, water, and soil.

Air Temperature

Globally, air temperatures on Earth have warmed by about 0.75°C (1.5°F) since 1900 (Intergovernmental Panel on Climate Change 2014; 2018) and by nearly 1.1°C (2°F) in the Pacific Northwest (May et al., 2018; Figure 4.1). This warming is attributable to human-caused emissions of greenhouse gases, such as CH₄, N₂O, and CO₂ (Intergovernmental Panel on Climate Change 2018; Oreskes 2004). The Salish Sea region has shown a warming trend in recent years (1980 to present), with average temperatures for almost all years since 1980 above the 100-year average (Mauger et al. 2015). In 2015, during the “the Blob” heat wave event, the Salish Sea region experienced its warmest air temperatures on record at 1.9°C (3.4°F) above normal for the year and 3.4°C (6.2°F) warmer during the winter (May et al. 2018). Going forward, the projected average temperature increase over the next 25 to 50 years ranges from 2.0° to 3.3°C (4.2° to 5.9°F) (Mauger et al. 2015; PCIC 2018), signaling that the temperatures experienced in 2015 were a preview of projected change for this region (see Vignette 12, The Blob).

Those drivers and their impacts alter much more than just temperature in the marine environment by affecting ocean currents, salinity, water density, pH, and other structural elements of marine systems. Discussed below are several examples of physical and chemical impacts, how they force changes within other inter-connected elements, and how those changes impact ecosystems.

While warming from climate change is expected for all seasons and is projected to be greatest in summer (Mauger et al. 2015), wintertime warming air temperatures could lead to profound changes in snowpack, and in turn, to water delivery to the estuarine waters of the Salish Sea (Figure 4.2). For example, in 2015 the region experienced abnormally warm air temperatures throughout the year, which led to an extremely low snowpack, pronounced water scarcity, and wildfires. These types of impacts are predicted to increase in occurrence and severity over time.

Changes to temperature and precipitation will have impacts on freshwater delivery in terms of availability, scarcity, and timing. For each 1°C (1.8°F) of air temperature warming, peak snow-water equivalent (the amount of water contained within the snowpack, which can be thought of as the depth of water that would theoretically result if the entire snowpack was melted instantaneously) in the Cascades is expected to decline 22% to 30% (Cooper et al. 2016).

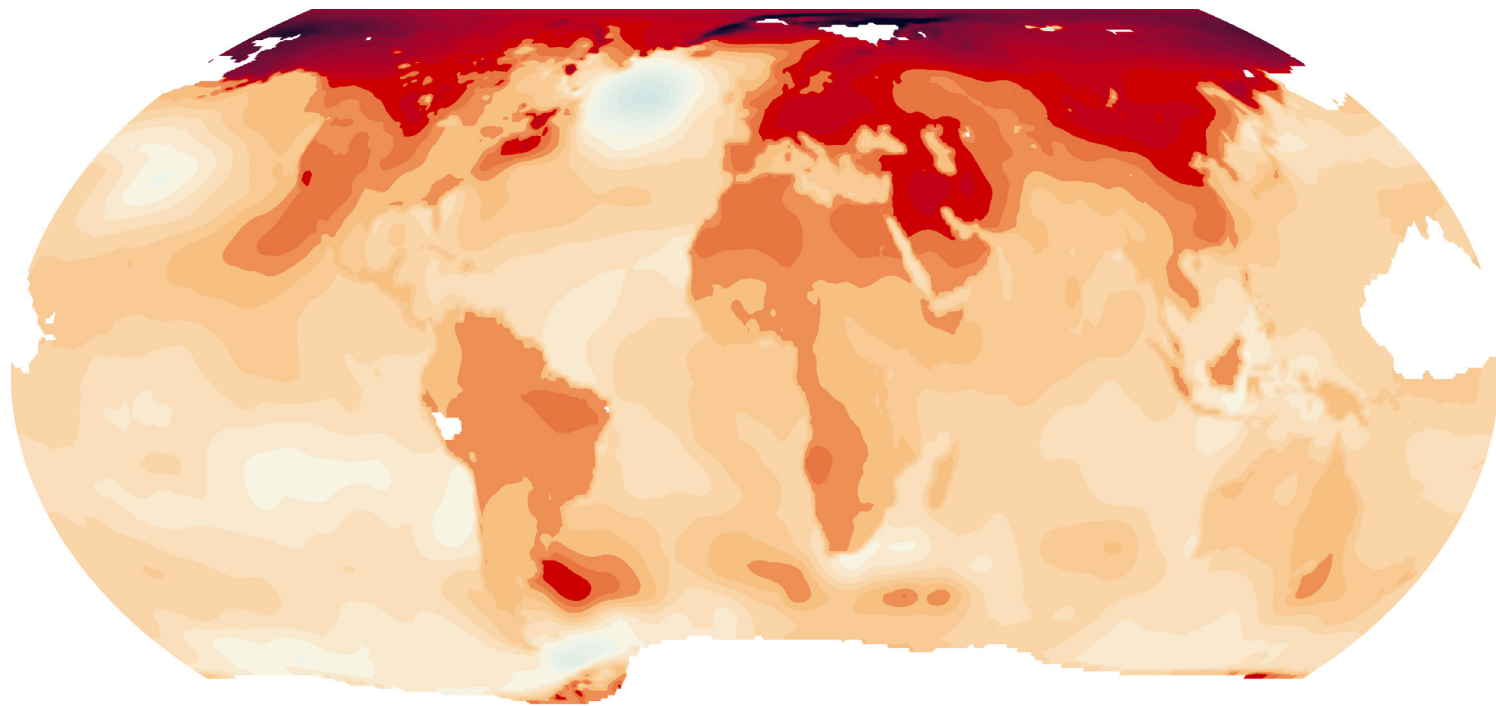


Figure 4.1. Global temperatures in recent years are some of the warmest on record. This static image of a dynamic map of Berkeley Earth data shows how the temperature average of the last five years compares with the years 1880 to 1899 (refer to the source to view an interactive map with this and other data). Source: Mooney & Muyskens (2019)

The loss of snowpack has implications for water delivery in the spring and early summer, as lower snowpack will mean less melt-off (volume of runoff) and earlier melt-off.

Warming air temperatures have affected and will continue to directly affect stream temperatures (Isaak et al. 2012). Temperature is one aspect governing the kinds of organisms that can live in freshwater systems and it impacts metabolic processes of these animals (higher temperatures typically involve higher metabolic costs; Clark & Fraser 2004). Additionally, temperature influences water chemistry by governing dissolution of minerals and gases (water at higher temperatures can hold less dissolved oxygen), which is an important consideration for aquatic life. Temperature effects in streams can be subtle increases over time or more pronounced short-term, discrete, or acute effects. For example, water temperature in the Fraser River has increased by an average of 3.3°C (5.9°F) over the last century (Riche et al. 2014), representing a gradual increase over time. Meanwhile, the number of days when Fraser River water temperatures exceed a threshold for salmon migration (believed to be 18°C, Martins et al. 2011) has increased over the last 50 years (Riche et al. 2014), representing an acute effect.

As global climate change continues, we are likely to experience similar combinations of persistent and acute increases in air, water, and soil temperatures, leading to complex changes in the biota dependent upon those systems.

Both persistent and acute temperature changes can impact stream chemistry, biota, and more, but the impacts on the receiving waters of the Salish Sea are currently not well understood. Model downscaling (the use of large-scale climate models to make predictions at local scales) is necessary to resolve predictions for coastal areas that often have different dynamics than the open ocean. Local predictions of physical conditions can then be used to investigate impacts to biota at the local scale. Although the complex oceanography within inland waters like the Salish Sea makes predictions particularly challenging, it's clear that impacts from warming freshwater will likely be most pronounced in areas where freshwater and saltwater mix in river-mouth estuaries. For example, recent modeling work in the Snohomish River estuary projected a 4°C (7.2°F) increase by the end of the century in the estuary headwaters (upriver region) and a 2°C (3.6°F) increase in temperature in the mixing zone in Possession Sound (seaward region; Khangaonkar et al. 2019).

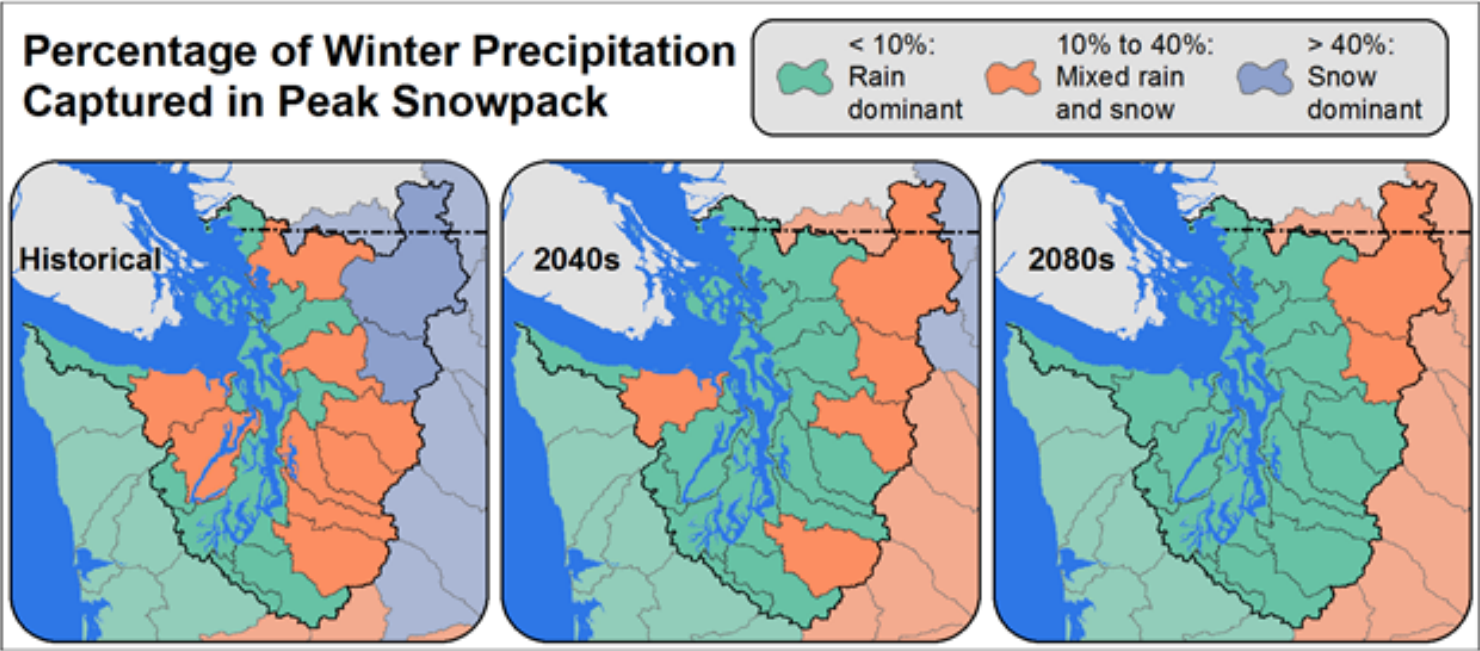


Figure 4.2. Percentage of winter precipitation captured in peak snowpack. Models project a dramatic shift to more rain-dominant conditions in Puget Sound watersheds from a recent historical time period (1970-1999) forward 100 years to the 2080s. Maps indicate current and future watershed classifications based on the proportion of winter precipitation stored in peak annual snowpack. Source: Mauger et al. (2015)

Freshwater Delivery

Inflow from the Fraser River, Skagit River, and the many smaller rivers emptying into the Salish Sea, together with direct precipitation, drives many aspects of physical oceanography within the inland waters. These include stratification and saltwater dilution. Most importantly in the Salish Sea, incoming freshwater (mostly from the Fraser River) helps drive estuarine circulation (Masson & Cummins 2000), which transports organisms, circulates nutrients and oxygen, and transports sediments. Thus, changes in freshwater delivery can have impacts on physical gradients (e.g., water density) and biological processes within the estuary.

As air temperatures continue to increase, there are two aspects to precipitation that will directly impact freshwater delivery, and thus the estuarine waters of the Salish Sea: 1) more intense precipitation events will periodically increase freshwater delivery and 2) increasing rain (rather than snow) in alpine areas will result in increased freshwater delivery, especially during the winter months. Regarding the first impact, intense precipitation events are historically atypical because the region normally receives rainfall as a steady drizzle or light rain over the winter months rather than episodic torrential downpours (multiple inches in a 12-hour period). An increase in rain event intensity means more rainfall in short periods of time, increasing the variation in water delivery timing (Ward et al. 2015) and increasing runoff and flooding as water flows from the upper watersheds, through the coastal lowlands, and into the Salish Sea.

For the second effect, snowfall is expected to decline as temperatures warm, and will be replaced with rain events in the mountains (Figure 4.3). This will result in increased winter streamflow, as snowpack typically serves as a water reservoir to hold freshwater until seasonal temperatures warm enough to begin seasonal

melting. This is a critically important disruption because snow and ice serve as hydrological stabilizers, reducing variation in freshwater flow from the mountains to the coasts (Johannessen & Macdonald 2009). Without this reserve of frozen water built up in snowpack over the winter months, spring freshets (the annual peak in flow associated with snowmelt) in major snow-influenced rivers, such as the Fraser and Skagit Rivers, will likely be reduced. In short, water delivery will increase throughout the winter season, but will be seasonally reduced during the spring melt-off. This change will likely have significant implications for estuaries, leading to changes in the circulation and transport of nutrients, oxygen, sediment, and biota.

Another aspect of a changing hydrograph (freshwater discharge over time) is the projection of a significantly lower peak flow occurring much earlier in the year (Figure 4.3). Johannessen and Macdonald (2009) show this to be about 24 days earlier by 2080 than during the 1961 to 1990 reference period for the Fraser River. An earlier study conducted more broadly in the Pacific Northwest found shifts of 10-30 days earlier already occurring in their 50-year period of study, 1948 to 2000 (Stewart 2004). These studies provide an indication of changes in water delivery already occurring and projected for the future.

How changes in streamflow timing will influence the estuarine waters of the Salish Sea is not well understood and will likely vary by river system and location. For example, a modeling study in the Snohomish River estuary (Yang et al. 2013) suggests that salinity intrusion points will change with changing river discharge and sea level rise. However, given the dynamic nature of estuaries with respect to salinity, the impacts of these changes to biota are unknown and may depend upon the time scales at which they occur.

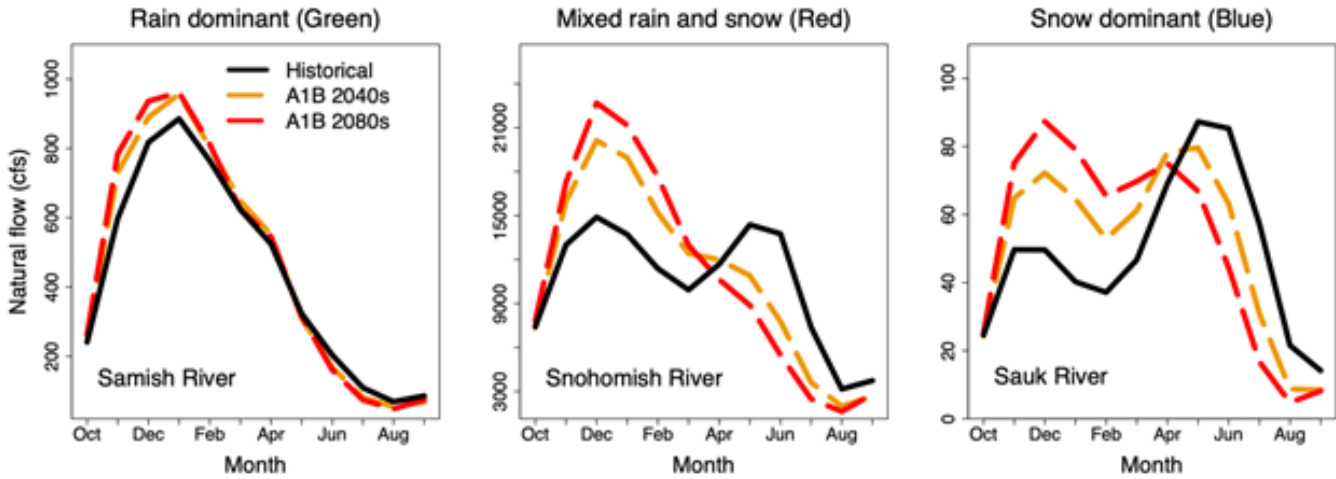


Figure 4.3. Changing freshwater discharge in three different watershed types. Colors in graph titles refer to those in Figure 4.2, which provides a spatial depiction of rain dominant, mixed rain and snow, and snow dominant watershed types. Graphs indicate average historical (1970-1999, black line) and future average monthly streamflow. Average projected future conditions are from ten global climate models during two time periods: the 2040s (2030-2059) and the 2080s (2070-2099) using a moderate greenhouse gas scenario (A1B). Streamflow is projected to increase in winter and decrease in spring and summer for all basin types, with the biggest changes occurring in mixed rain and snow watersheds. Source: Mauger et al. (2015); data from Hamlet et al. (2013)



Racehorse Falls in Deming, WA
Photo: Nick Pinkham

Sea Water Temperature

Global ocean surface waters have warmed between 0.5 and 1.0°C (0.6-1.8°F) since 1970, with warming observed at all depths. Due to the ocean’s heat capacity and circulation, the rise in ocean temperatures lag those of air, river, and lake water (Intergovernmental Panel on Climate Change 2007). In addition, changes in ocean temperature are not evenly distributed

across the globe. Time-lapse animations and static maps, like the series shown in Figure 4.4, make it clear that the Northern Hemisphere has disproportionately warmed, with some of the highest rates of warming across the globe observed in the North Pacific (+5.0 to 6.0°C; Figure 4.5).

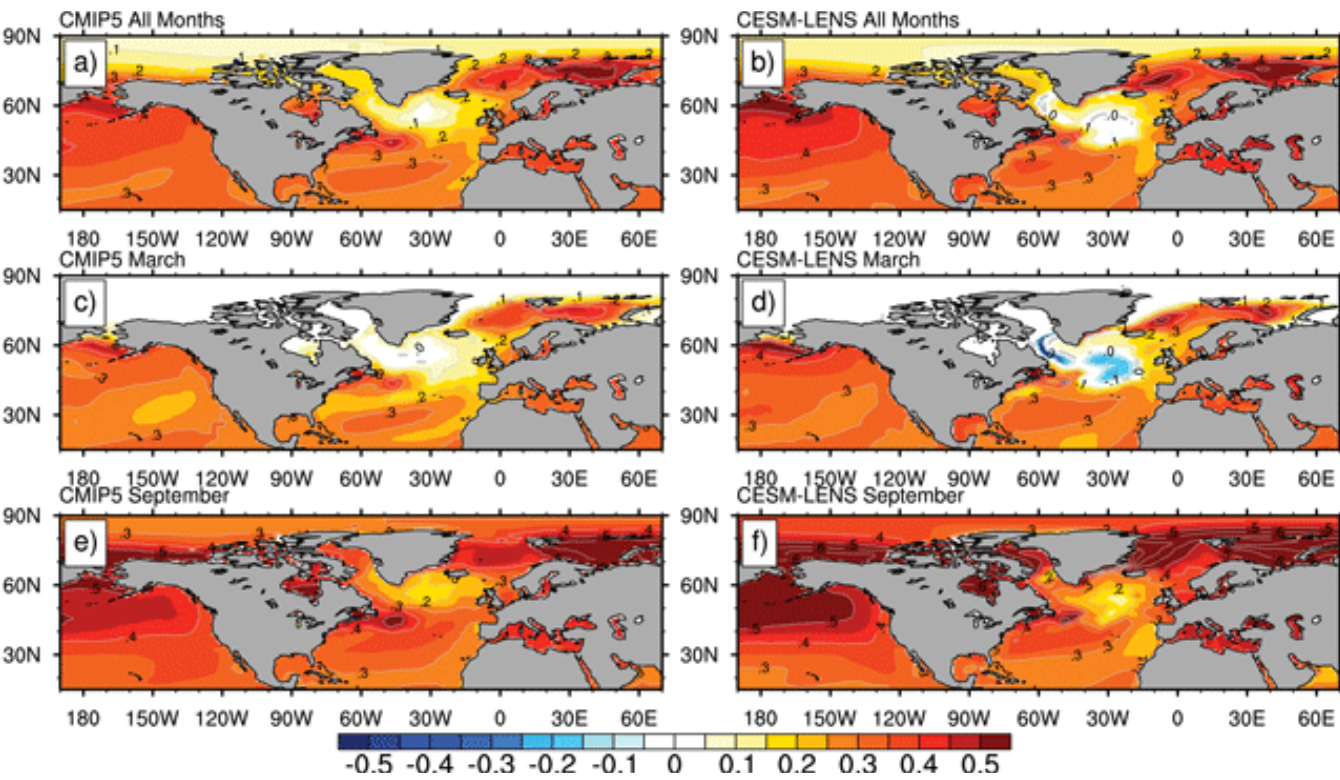


Figure 4.4. Ensemble mean sea surface temperature trends predicted from climate models (CMIP5 and CESM-LENS) over the period 1976-2099. Trends are shown for all months (a, b), for March (c, d), and for September (e, f) based on CMIP5 (a, c, and e) and CESM-LENS (b, d, and f). Color bar indicates trends in °C per decade with positive values in shades of red and negative values in shades of blue. Only trends that are significant at a 95% level using a Mann-Kendall test are shown. Trends are positive and significant in most areas except the North Atlantic and Arctic Oceans in March. Source: Alexander et al. (2018)

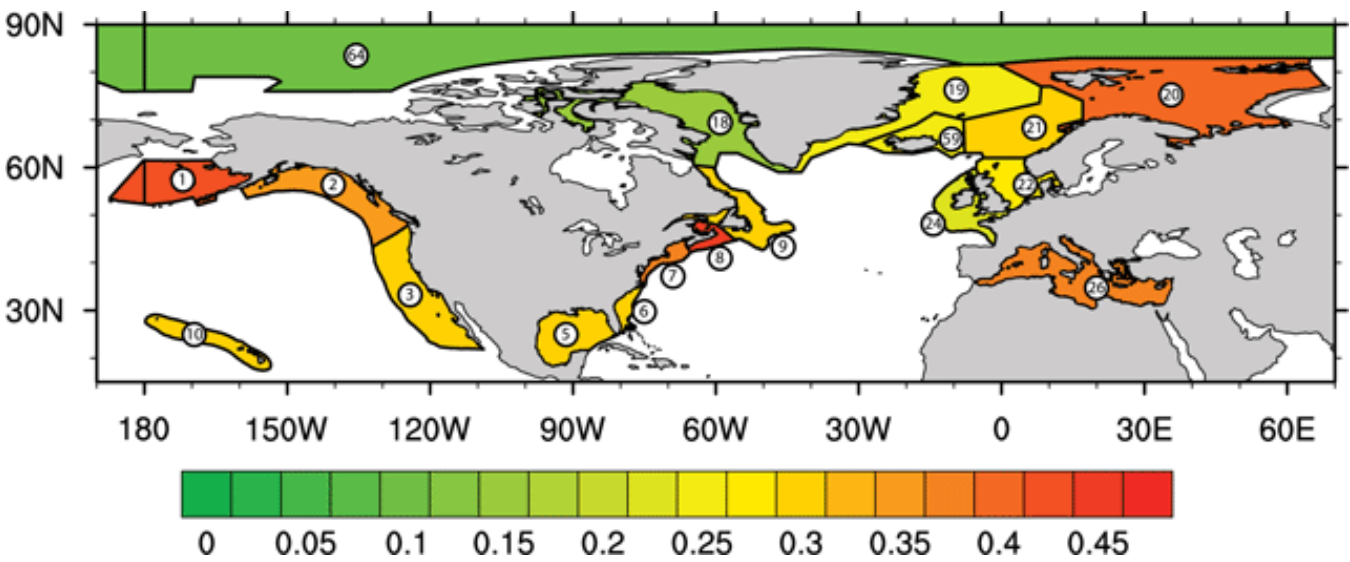


Figure 4.5. Sea surface temperature trends in Large Marine Ecosystems in the northern hemisphere. Colors denote the climate model (CMIP5 ensemble) mean area-averaged SST trends (°C per decade) during 1976–2099. All trends are significant at the 95% level using a Mann-Kendall test. Regions are numbered following the LME convention: 1) Bering Sea, 2) Gulf of Alaska, 3) California Current, 5) Gulf of Mexico, 6) Southeast US Shelf, 7) Northeast US Shelf, 8) Scotian Shelf, 9) Newfoundland-Labrador Shelf, 10) Hawaii, 18) West Greenland, 19) Greenland Sea, 20) Barents Sea, 21) Norwegian Sea, 22) North Sea, 24) Celtic-Biscay Shelf, 26) Mediterranean, 59) Iceland Shelf and Sea, and the 64) Central Arctic. Source: Alexander et al. (2018)

In the Salish Sea, one of the best time-series of sea surface temperature (SST) is from the network of British Columbia lighthouse stations (Fisheries and Oceans Canada 2021). Daily observations of SST and salinity started at the Pacific Biological Station in Departure Bay, BC, in 1914. Observations were made daily using the time-tested technique of measuring seawater collected in a bucket. This sampling apparatus was lowered into the surface water at or near the daytime high tide and the temperature and salinity were measured. The methodology has remained the same throughout the time-series for consistency, offering one of the best long-term records of measurement in the region (White et al. 2016). More recently, researchers have used satellite (MODIS) derived temperature data to measure temperature across broader areas (Amos et al. 2015). Monthly averaged satellite data show that trends in SST at two sites

in the Strait of Georgia are very similar to the Lighthouse measurements; this correspondence supports spatial extrapolation of the Lighthouse measurements to the broader basin, extending further the value of the time-series.

The stations in the Strait of Georgia show a mean increase in SST of about 0.56°C per decade (Amos et al. 2015). This is higher than the global average (Intergovernmental Panel on Climate Change 2007; Solomon et al. 2009) and contrasts markedly with the trends from the more northern stations in British Columbia, which have shown less warming. The warming trends of the southern stations are significant in all months of the year but are most evident during summer (July–September). The summertime anomalies in temperature at Active Pass are significantly correlated with the temperature of Fraser River water, suggesting that warming freshwater in

this major tributary has an influence as it flows into the Salish Sea. Temperature differences between the Strait of Georgia and the outer continental shelf are increasing in time, especially since 2000. At present rates of SST rise, the southern coastal waters of British Columbia are projected to be about 3°C warmer by the end of the 21st century.

The Salish Sea Model (Figure 4.6; see Vignette 13, Salish Sea Model) is a complex hydrodynamic model developed for the Salish Sea and serves as a tool with which to assess changes in Salish Sea conditions

given some inputs to forcing (climate or other) (Khangaonkar et al. 2012). As part of a recent study (Khangaonkar et al. 2019), the authors used climate forcing to determine changes in circulation, sea level rise, and other attributes in the Salish Sea. Similar to work from the Strait of Georgia (Amos et al. 2015), their model showed a projected increase in sea surface temperature of 2.6°C by the end of the century. Mixing and circulation driven by ocean water mediate some of the temperature increases resulting from increasing air temperature and temperatures of inflowing freshwater, but as the ocean warms, the mediating properties may diminish.

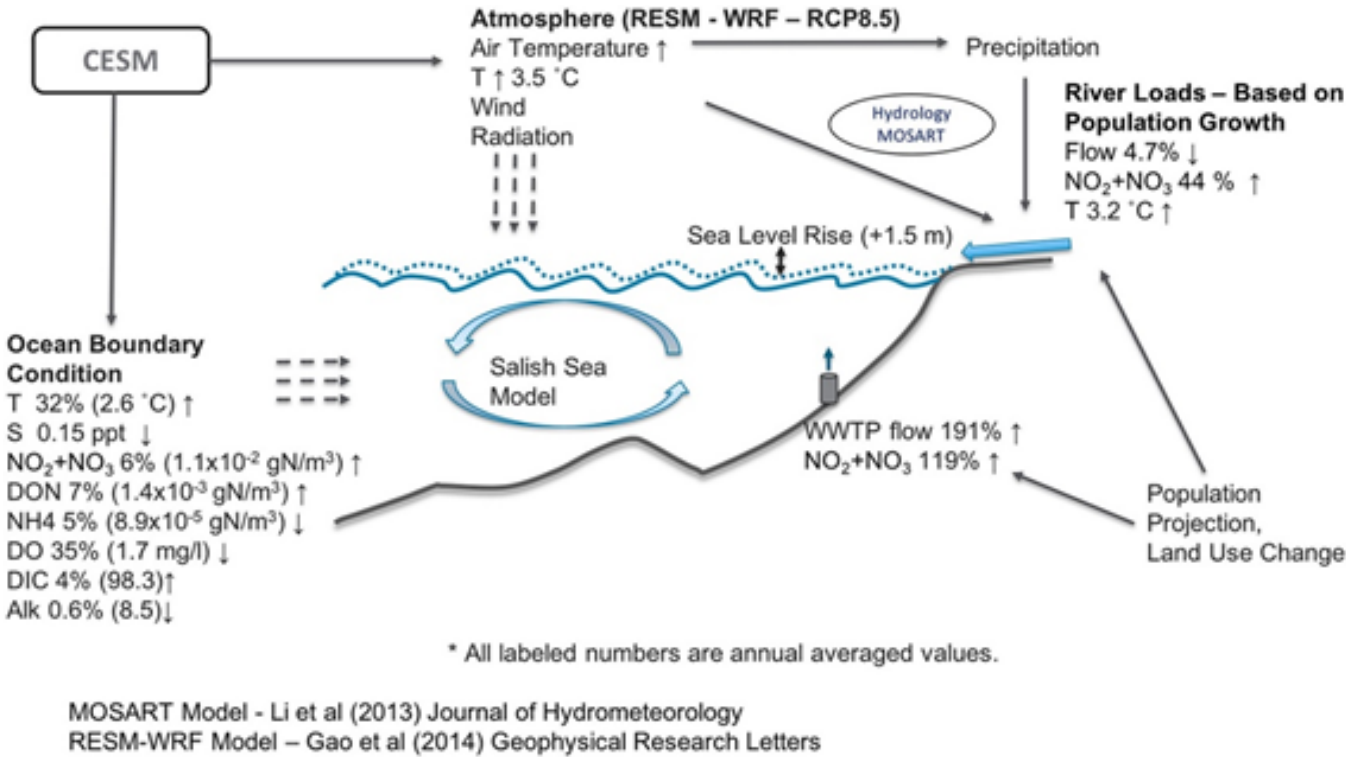


Figure 4.6. The Salish Sea Model is a three-dimensional computer tool that can simulate hydrodynamic and water quality processes in the Salish Sea. Shown here is a summary of the projected changes for temperature, salinity, freshwater inflows, and water quality variables for the future (75 years from now, 2095) relative to inputs for 2000. The model uses climate scenario RCP8.5 and includes several input models including: CESM = Community Earth System Model; RESM = Regional Earth Systems Model; WRF = Weather Research and Forecasting; and MOSART = Model for Scale Adaptive River Transport. Variables include: T = temperature, S = salinity, NO₂ and NO₃ = Nitrite and Nitrate (nutrients), DON = dissolved organic nitrogen; NH₄ = Ammonium, DO = dissolved oxygen; DIC = dissolved inorganic carbon; Alk = Alkalinity, and WWTP = wastewater treatment plant. Source: Khangaonkar et al. (2019)

Anomalies

Climate data, whether air or sea surface temperature or other metrics, are often presented as anomalies. An anomaly is the deviation in a quantity from its expected value, such as the difference between an observation (measurement) and a mean, or the difference between a mean and a model prediction. It is important to understand the reference period used to understand the scale of change. In climate science, the present-day climate is compared to a period in the recent past (typically 1980 to 1999, but other time

periods like 1950 to 2000 may be used). Current observations or model predictions for the future are generally shown as deviations from the average for this reference period and will be represented as values greater than or less than zero, with zero being the mean from the reference period and therefore a form of baseline from which to compare. Datasets that are local (for example, from the Salish Sea as described in this report) or don't have long time-series may use different reference periods, but still present data as anomalies.

Our understanding of the effects of climate change, particularly warming sea surface temperatures, is aided by natural experiments. The marine heat wave in the northeast Pacific Ocean of 2014 to 2016, known as the “Blob” is one such natural experiment. While the Blob has subsequently diminished; it's important to note that the effects of that event persisted in observed biota on the coast for several years after the most extreme temperature rise (Sutherland et al., 2018).

A new heat wave was observed in the fall of 2018 due to delayed and reduced winter cooling (Boldt et al. 2019), and it continued into 2019, prompting concerns about the return of very high sea surface temperatures in the region. But weather events in the fall of 2019 resulted in the warm mass being driven offshore into the North Pacific. The frequency and duration of these warm water events will be of much interest to scientists in the coming years.

The Blob

Strongly positive temperature anomalies developed in the northeast Pacific Ocean during the winter of 2013–2014. These anomalies were caused by lower-than-normal rates of the loss of heat from the ocean to the atmosphere and of relatively weak cold advection in the upper ocean. Both of these mechanisms can be attributed to an unusually strong and persistent weather

pattern featuring much higher-than-normal sea level pressure over the waters of interest. The region of warm sea surface temperature anomalies subsequently expanded and reached coastal waters in spring and summer 2014 and persisted through 2016. This warm water mass became known as the “Warm Blob” or the “Blob.” (See Vignette 12, The Blob, for more detail.)

The consequences of short-term and long-term changes in water temperature for the Salish Sea are not yet fully understood. What is apparent is that the inland waters of the Salish Sea are unique and do not follow lockstep with coastal oceanographic phenomena, but they do exhibit some of the same signals. The influence of local urbanization in the region's many watersheds and the variable inputs of freshwater are defining features of the system, but those features also make it challenging to predict or fully resolve complex interactions between atmospheric and oceanographic conditions (Roop et al. 2020). Additionally, reductions to circulation driven by climate change, and the system's unique and varied oceanography, could exacerbate effects of increasing temperatures at local scales.

We do know that warming sea water temperature interacts with other physical, chemical, and biological processes to shift species distributions

(Hazen et al., 2013), increase metabolic costs (Deutsch et al. 2015), change phenology (the timing) of events such as phytoplankton blooms or migrations (Brown et al. 2016), and destabilize food webs (Nagelkerken et al. 2020). In the Salish Sea, these changes are happening simultaneously, with impacts to salmon (Hinch et al. 1995; Shelton et al. 2020), phytoplankton (Moore et al. 2008), and likely many other species that are yet unstudied. Additionally, increasing sea water temperature increases susceptibility to marine diseases (Harvell et al. 2019; Burge & Hershberger 2020; and see Vignette 14, Eelgrass Wasting Disease) and amplifies bioaccumulation of contaminants (Alava et al. 2018). Without a doubt, many effects are occurring simultaneously and, in some cases, synergistically.

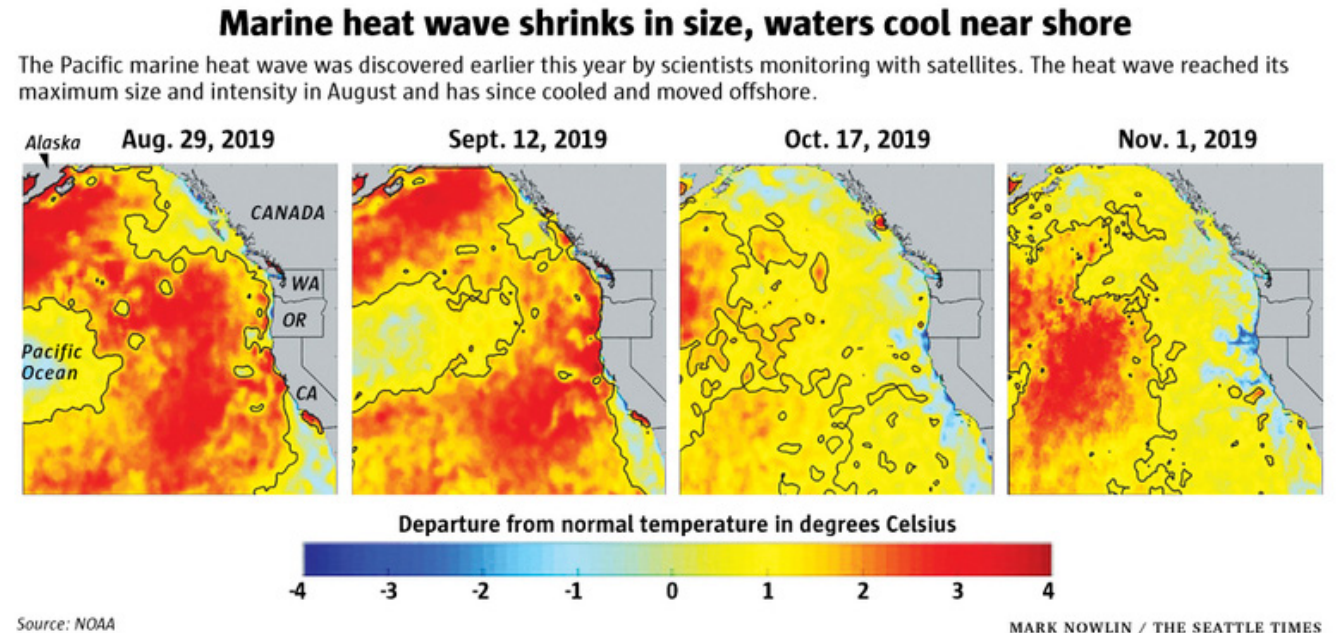


Figure 4.7. A new marine heat wave after the Blob in 2014-2016. After the Blob event in 2014-2016, a new marine heat wave set in during the summer of 2019 but dissipated that autumn. Source: Mark Nowlin & the Seattle Times (2019)

Ocean Acidification

Ocean acidification refers to the chemical changes in the ocean caused by the absorption of CO_2 from the atmosphere (Figure 4.8). Predictions for the next 100 years indicate that the oceans will continue to absorb CO_2 , further increasing ocean acidity. Since the beginning of the Industrial Revolution when anthropogenic carbon emissions began to increase significantly, the global average pH of surface ocean waters has declined by 0.1 pH units from an average of 8.2 to 8.1. This may not

seem like much, but the pH scale (measured from 0-14, with lower values representing acidic conditions), like the Richter scale, is logarithmic, meaning this change represents an approximate 30% increase in acidity (Pacific Marine Environmental Lab 2021). Estimates of future CO_2 levels, based on business-as-usual emission scenarios, indicate that by the end of the 21st century, the surface waters of the ocean could show acidity levels 1.5 times what they were prior to the Industrial Revolution.

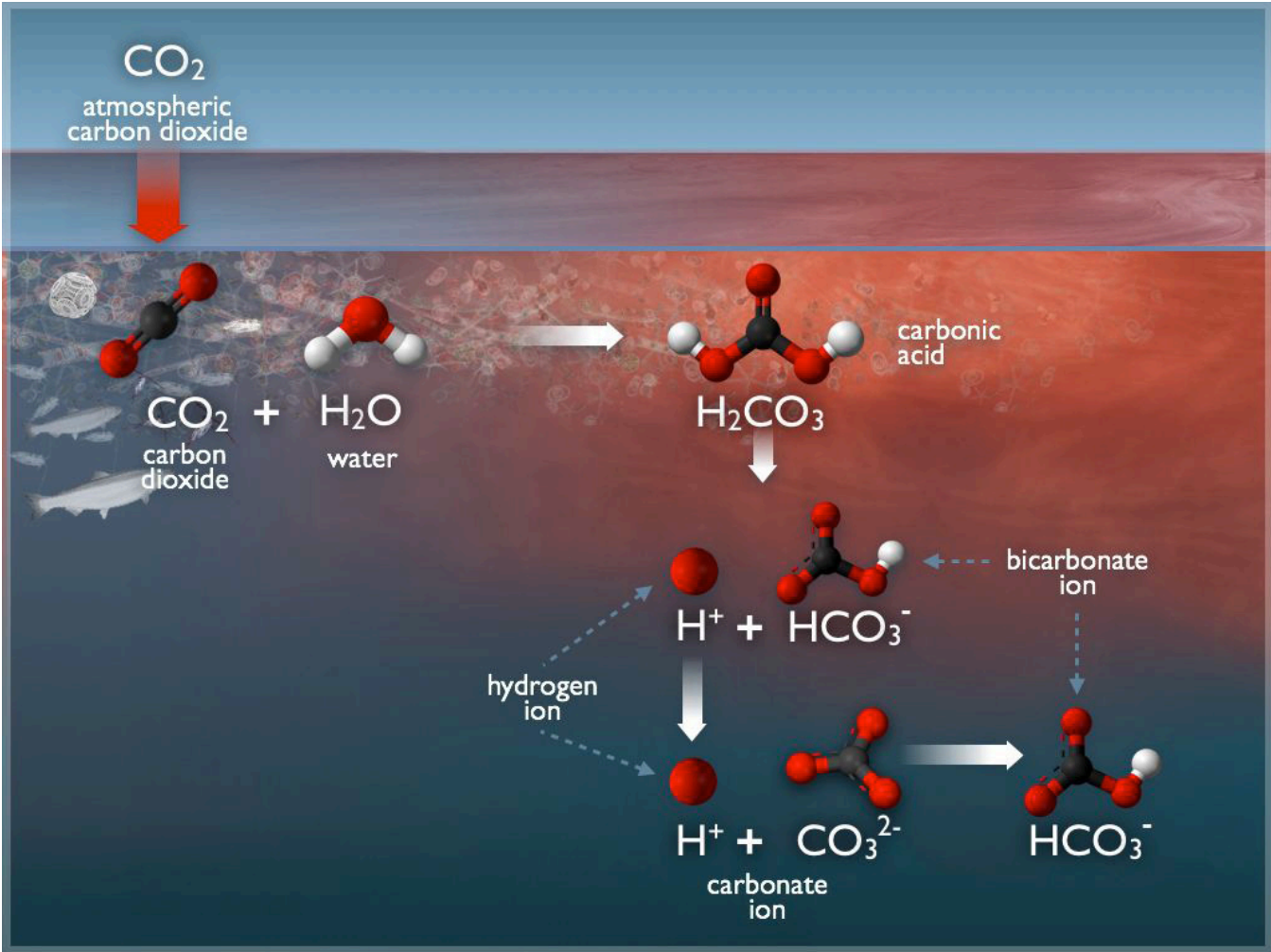


Figure 4.8. Carbonate dynamics in the Salish Sea are driven by a number of physical processes occurring along the Pacific Coast and in the inland waters. CO_2 from the atmosphere is absorbed by the ocean and mixes with seawater to form carbonic acid. This carbonic acid then quickly dissolves to form an acid (H^+ ion) and bicarbonate (HCO_3^-), which is a base. This is the process known as ocean acidification. Source: Center for Environmental Visualization (2014)

Pacific Northwest coastal waters are among the most acidified worldwide (Feely et al. 2010; Feely et al. 2012; Mote et al. 2014). In the Salish Sea, pH is largely regulated by natural mixing, circulation, and biological processes. The geography, bathymetry, and natural physical forcing in the Salish Sea put it at similar risk of acidification as the nearby coastal waters. The features contributing to the risk of ocean acidification include incursion of upwelled waters that are naturally low in pH and rich in CO₂ (Crummett et al. 2020), restricted circulation within the Salish Sea caused by shallow sills between basins, inputs of naturally low pH river water, and inputs of nutrients from humans (Cai et al. 2021).

Ocean acidification currently plays a small but significant role in reducing the pH of Salish Sea waters and is somewhat seasonally driven. At La Push, WA, the NANOOS (Northwest Association of Networked Ocean Observing Systems) buoy monitors pH and several other water quality parameters (NANOOS 2021). The data from this buoy show a seasonal pattern to pH, with more acidified (lower pH) water present in the winter months compared with the summer months (Figure 4.9), observations also made in the Northern Salish Sea (Evans et al. 2019). This seasonal pattern is driven in part by phytoplankton production taking up CO₂ and thereby modulating pH during the summer months (Lowe et al. 2019).

In addition to reduced seawater pH, there are three other major chemical changes caused by CO₂ absorption: increase in inorganic (total) carbon, reduced carbonate ion concentrations,

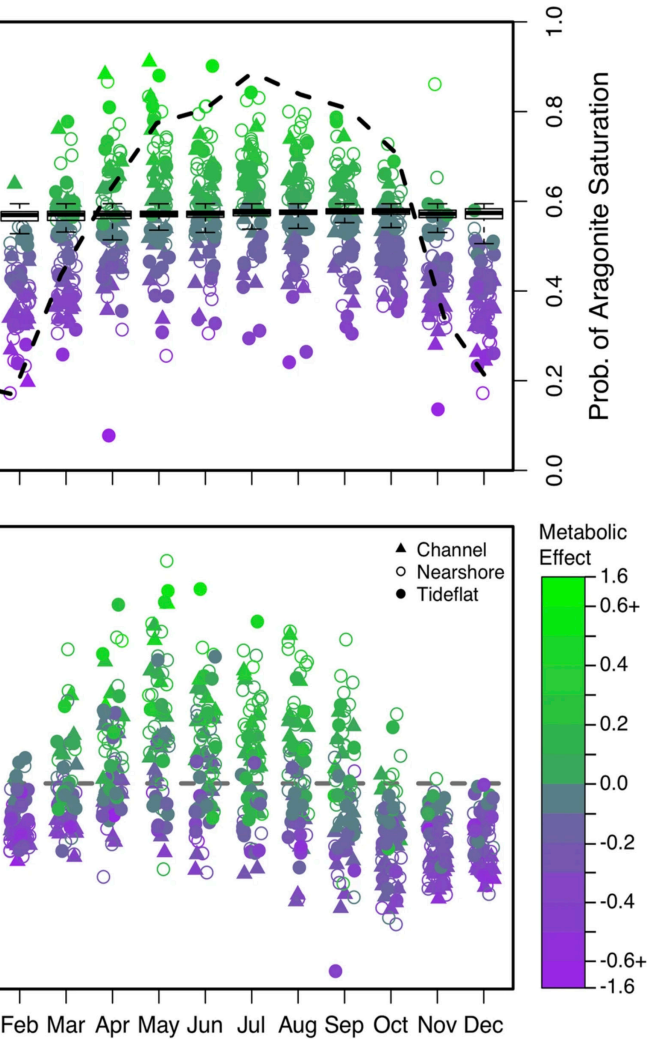


Figure 4.9. Seasonal variation of (a) observed pH (b) and dissolved oxygen (%) for sites in Washington waters. (a) Mean monthly site-specific pH (colored points), distribution of predicted standardized ('atmospheric equilibrium') pH across all sites for each month (black boxplots), and the probability of observing aragonite supersaturation within the region in a given month (dashed line corresponding to right axis). (b) Mean monthly site-specific dissolved oxygen saturation. Color of points in (a) and (b) corresponds to the magnitude of the ecosystem processes (metabolic effect) on pH (observed pH minus 'atmospheric equilibrium' pH) as indicated in the legend. Shape of points indicates habitat of the site: triangle = channel, open circle = nearshore, filled circle = tideflat. Source: Lowe et al. 2019.

and reduced saturation states of biologically important calcium carbonate minerals. Calcium carbonate minerals are the building blocks for the skeletons and shells of many marine

organisms and aragonite is the primary mineral used as an indicator of ocean acidification. The formation of calcium carbonate is sensitive to the concentration of carbonate ions in seawater. In most areas of the coastal ocean, there is ample calcium carbonate ion and therefore abundant material for calcifying organisms to build their skeletons and shells. However, ocean acidification is causing carbonate ion to decline, which is likely to negatively affect the ability of some organisms to produce and maintain their shells. There is already evidence of reduced calcification among pteropods (pelagic mollusks) in the Salish Sea (Bednaršek et al. 2020a). Many organisms at the base of the food web rely on calcium carbonate to build shells, meaning any disruption to these abundant organisms will ripple throughout the marine food web.

Key biological processes, including photosynthesis, growth, respiration, recruitment (the addition of juveniles to a population), reproduction, and behavior are sensitive to high CO₂ and low pH (Whitely-Binder & Washington State Blue Ribbon Panel on Ocean Acidification 2012). While ocean acidification is generally considered a negative impact in marine ecosystems, in some cases, increased carbon may benefit ecological processes. For example, increases in total carbon can stimulate photosynthesis, resulting in blooms when other limiting nutrients are also available (Boyd et al. 2018). This increase in primary production can also positively affect zooplankton communities (Taucher et al. 2017), although this has not been demonstrated for the Salish Sea (McLaskey et al. 2019). In some places, phytoplankton blooms may include harmful algal species, posing a health risk or producing unknown consequences for other organisms (Hattenrath-Lehmann et al. 2015). These and other studies are identifying direct impacts of ocean acidification to biota and clarifying the mechanisms causing change, with much more yet to be learned.

Ocean acidification has the potential to directly affect a wide range of organisms in the Salish Sea, from primary producers including phytoplankton and seagrasses, to marine invertebrates (e.g., shellfish) and vertebrates (e.g., fishes). Increased concentrations of CO₂ in the marine environment impede calcification processes for organisms like clams and oysters (Figure 4.10; Waldbusser et al. 2015) and can influence the physiology of marine organisms by changing their internal acid-base balance, potentially leading to changes in protein synthesis, growth, development, and neurophysiology—and reduced oxygen transport capacity (Kroeker et al. 2013). Invertebrate prey important to salmon and herring, including gammarid amphipods, harpacticoid and calanoid copepods, euphausiids, and decapod larvae could be also affected by increased ocean acidification. Recent work on Dungeness crab larvae on the Pacific Coast showed risk of carapace dissolution (chemical degradation of the shell, resulting in structural deformities), which has implications for growth (Bednaršek et al. 2020a). Dungeness crab is a valuable and important fishery in the region, and reduced condition of larvae could have serious impacts to the sustainability of the fishery. Using predictions from the Salish Sea Model, the same researchers identified South Puget Sound as a potential hot spot for damage from acidification for larval crab, driven by the uptake of atmospheric CO₂ (Bednaršek et al. 2020b).

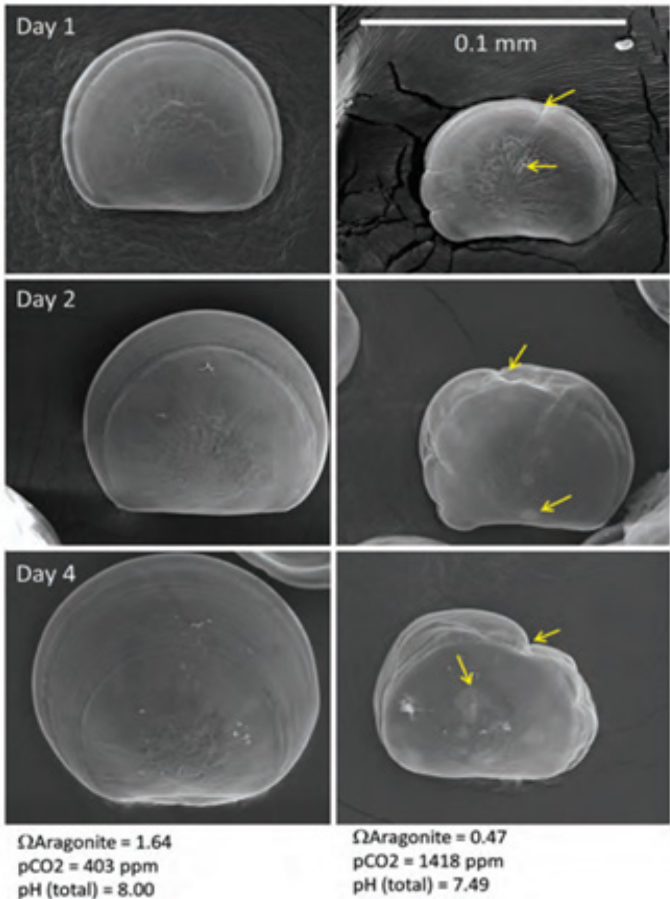
There are also potential direct effects on fish, which have been shown to experience olfactory disruption and other physiological impacts as a result of acidified waters (Williams et al. 2019). Many estimates of species at risk from ocean acidification are based on projections from laboratory exposure experiments or laboratory experiments in combination with model predictions. With the exception of pteropods (Bednaršek et al. 2020a), few studies have

clearly demonstrated changes in abundance or condition for Salish Sea species in the wild as a direct consequence of changes in ocean chemistry from increasing CO₂, but the decrease in ocean pH from anthropogenic CO₂ is well documented and the projected decrease in pH is well understood. However, the biological response to these changes is much less clear and is the ongoing focus of research efforts around the world and here in the Salish Sea. Anthropogenic acidification due to eutrophication (described further below) is where nutrients of anthropogenic origin enhance organic matter production in shallow coastal areas, which is then respired to produce CO₂. While not as prevalent a mechanism in the Salish Sea as in other regions (e.g., Chesapeake Bay; Zimmerman & Canuel 2000), this type of acidification is observed locally. An example is from the southern part of Hood Canal, Washington where there is concern that nutrients from terrestrial runoff may stimulate

additional production of organic matter that is respired to CO₂ (Feely et al. 2010). Irrespective of anthropogenic nutrient inputs, seasonal phytoplankton cycles (Pelletier et al. 2018) and annual variability in circulation will also influence CO₂ uptake and pH in inland waters. Understanding the synergistic responses to elevated CO₂ and impacts when combined with low oxygen, warming SST, and localized eutrophication is necessary to fully understand the impacts of acidification.

There are concerns about future impacts of acidification in oceans and the Salish Sea, given the predicted trajectory for atmospheric CO₂ and long-term local trends in seawater pH. The extremely rapid and accelerating pace of change in ocean pH and the susceptibility of a wide variety of taxa to changes in ocean carbon chemistry suggest that while the precise effects of ocean acidification are largely unresolved, they could substantially compound throughout the food web. The indirect effects of ocean acidification are likely to be even more pervasive, as are the interactions between ocean acidification and other effects of global climate change. For example, deoxygenation and increasing seawater temperatures will be complex, with synergistic or antagonistic responses that are typically difficult to measure in the field (Gao et al. 2019). Experimental work and field-based investigations on the cumulative effects of climate change are underway, but deserve increasing attention given the accelerating pace of the impact.

Figure 4.10. Pacific oyster larvae from the same spawn, raised by the Taylor Shellfish Hatchery in natural waters of Dabob Bay, Washington, under favorable total pH = 8.00 (left column) and unfavorable total pH = 7.49 (right column) carbonate chemistry. Under more acidified conditions (right column) development of shell is impaired; arrows show defects (creases) and some features (light patches on shell) that are suggestive of dissolution. The scale bar in the upper right panel is 0.1 mm, or approximately the diameter of a human hair. Source: Whitely-Binder & Washington State Blue Ribbon Panel on Ocean Acidification (2012); photo credit: Brunner/Waldbusser



Clam nets on a beach near Shelton, WA
Photo: Duane Fagergren

Dissolved Oxygen

To survive, most marine organisms must have sufficient levels of dissolved oxygen (DO) in the water. Oxygen (O₂) enters the water through two natural processes: diffusion from the atmosphere and photosynthesis by phytoplankton and aquatic plants. The mixing of surface waters by wind and waves increases the rate at which oxygen from the air can be dissolved or absorbed into the water. Cold water can hold more oxygen than warm water, but dissolved oxygen concentrations are also driven by biological processes. While oxygen is consumed by animals throughout the ocean, the majority of consumption is caused by bacterial respiration of organic matter as it decomposes. These and other complex interactions among physical, chemical, and biological processes ultimately determine DO concentrations.

The processes and dynamics governing DO in the Salish Sea are important to understand because decreases in dissolved oxygen are a concern for maintaining aquatic life. As briefly explained below, decreases in DO manifest in three different forms: 1) global deoxygenation, 2) naturally occurring oceanic low-oxygen zones, and 3) eutrophication-induced low oxygen in coastal ecosystems. The mechanisms that drive each of these forms of reduced DO are distinct, but also all interrelated in the ecosystem.

Global Ocean Deoxygenation

Deoxygenation of the open ocean is one of the major marine manifestations of global climate change. Global deoxygenation is due largely to changing ocean currents. Oxygen minimum and limiting zones (natural areas of oceanic low oxygen) may incur into coastal waters like the Salish Sea. When these low-oxygen ocean waters mix with coastal low-oxygen waters, dissolved oxygen conditions worsen locally. Those variations in marine oxygen

concentrations can induce major changes to remineralization processes (chemical breakdown of particles) and associated sources and sinks of important nutrient elements, such as nitrogen, phosphorus, and iron in the water column and underlying sediments (Oschlies et al. 2018). The consequences of deoxygenation on water chemistry in the Salish Sea are largely unknown but there is evidence from other regions that dissolved oxygen loss has potentially broad impacts on pelagic and benthic fisheries, tourism, and ocean nutrient cycling (Schmidtke et al. 2017).

According to a recent estimate, the ocean lost 2% of its oxygen inventory between 1960 and 2010 (Schmidtke et al. 2017; Oschlies 2019). While increasing global ocean temperature is often cited as the cause, changing ocean circulation, mixing, and/or biochemical processes are also considered primary drivers for observed changes in ocean oxygen (Ito et al., 2017). In fact, Oschlies (2019) found that only about 15% of the oxygen loss is attributed to lower solubility of O₂ in warmer sea water (due to the direct effects of warming sea water), while a greater proportion of the decline (>50%) is due to changes (in most cases a slowing) in circulation and mixing resulting from temperature-driven increases in stratification. This stratification results in less exchange of high DO waters from the surface layer to the deeper bottom water. While rising global ocean temperatures may be the ultimate cause of these changes, the processes are complex and vary considerably among locations.

Overall, deoxygenation is an ongoing process and accompanies ocean warming and ocean acidification as one of the three major oceanic consequences of rising atmospheric CO₂ levels (Levin & Breitburg 2015). Decreasing O₂ in

Stratification

Ocean stratification is when water masses with different properties form layers that act as barriers to water mixing. The structuring properties are salinity and temperature, which drive differences in water density. The layers are normally arranged according to density, with the least dense water masses (typically fresher water) sitting above the denser layers (typically saltier water). Stratification can create barriers to mixing between layers, which can affect the primary production in an area. Phytoplankton need sunlight and nutrients, which accumulate in the deeper layers as particles are broken down, but without mixing, productivity is diminished because nutrients aren't available in the surface layer where sunlight is abundant. Additionally, stratification can cause anoxia or hypoxia, when oxygen-depleted waters (resulting from microbial processes consuming oxygen) are unable to mix with oxygen-rich surface waters. Indexes of stratification generally provide information about the difference in density between the surface water and water at depth.

subsurface waters is normally accompanied by increasing acidity on the British Columbia coastal shelf, and both trends are of great concern to marine life (Crawford & Peña 2013). Deoxygenation is expected to continue as increasing global temperatures reduce the capacity of the ocean to hold oxygen, decrease the degree of mixing in the upper water column, and reduce the ocean-overturning circulation.

Naturally Occuring Low-Oxygen Zones

Time-series have revealed a more extensive oxygen decline in the Northeast Pacific Ocean than in other parts of the ocean (Whitney et al. 2007). The marine waters that enter the Salish Sea via the Strait of Juan de Fuca and Johnstone Strait reflect conditions in the northeast Pacific Ocean that are influenced by complex global circulation patterns. In general, deep water off the Pacific Coast of North America is old (it has been circulating around the globe for centuries without contact with the atmosphere). This water is cold, dense, nutrient rich, and of most relevance here: oxygen depleted (Reid & Mantyla 1978; Hellya & Levin 2004).

On the continental shelf and slope off Washington and British Columbia, the lowest O₂ values are found in deeper waters (O₂ generally decreases with increasing depth and increasing water density in this region; Crawford & Pena 2013). But during summer, deep ocean water comes to the surface due to seasonal upwelling. Upwelling is driven by seasonal wind patterns that push surface waters away from shore, resulting in deep water rising to replace the water that has been displaced (see description at Center for Science Education 2008). Upwelling is an important component of oceanography and dissolved oxygen concentrations in the Salish Sea.

Ocean water typically enters the Strait of Juan de Fuca at depth and mixes due to tides and currents. As with ocean water on the continental shelf, the deeper portions of the Strait of Juan de Fuca tend to be low in DO, especially in the summer during strong upwelling. Dissolved oxygen at any depth is determined by vertical mixing and stratification, but it tends to be greater in surface waters and lower at depth as it enters the Strait of Georgia (Riche et al. 2015).

Once in the Salish Sea, oxygen-depleted but nutrient-rich ocean water mixes with warmer, oxygen-rich surface water, creating optimal conditions for seasonal productivity. But low dissolved oxygen within Salish Sea basin waters, partly imported from the shelf and partly driven by biological processes (e.g., carbon cycling) within the Salish Sea, could reduce benthic and pelagic habitat (Johannessen & Macdonald 2009) and disrupt biological productivity.

Coastal Eutrophication and Hypoxia

In addition to global changes in DO, declining oxygen concentrations have also been found in coastal oceans. These “hypoxic” zones are areas of very low O₂ concentration (<2 mg/L, compared with 8 to 12mg/L for oxygen-saturated waters). Coastal hypoxia is largely fueled by riverine runoff of fertilizers, but other anthropogenic inputs like failing septic systems and deposition of nitrogen emitted to the atmosphere by fossil fuel combustion are also important sources (Nixon 1995). The nutrients from these sources—primarily nitrogen and phosphorous, with nitrogen being the most limiting in marine ecosystems—contribute to eutrophication. Eutrophication is the process of increased organic enrichment of an ecosystem, generally through increased nutrient inputs (Nixon 1995). In short, nutrient input results in excessive primary production (phytoplankton and/or algae), which in turn leads to increased metabolism (bacterial activity), which is demanding of oxygen and results in local oxygen depletion. This hypoxia changes community structure (food webs and habitats) through remineralization, microbial processing, and respiration that can result in ocean acidification.

Some of the impacts of hypoxia beyond direct declines in available oxygen include increased sedimentation (from decomposing material that would have broken down if oxygen were available), reduced depth distribution

of submerged aquatic vegetation, and redistribution of fish and invertebrates to avoid low oxygen (hypoxic) or no oxygen (anoxic) areas. In coastal ecosystems like the Salish Sea, there is a delicate balance between having enough nutrient inputs and primary production to sustain life and a healthy food web, versus nutrient enrichment that accelerates primary production to the point of excess.

In many cases, eutrophication is a locally generated problem with local impacts. It typically results in declines in available oxygen, especially in the bottom waters. These hypoxic events can be episodic, occurring seasonally (most common in summer/autumn) in the coastal zone. In the Salish Sea, the overall anthropogenic contribution of nitrogen (typically thought of as “nutrient input”) is minimal relative to natural sources coming from ocean waters. While this makes widespread eutrophication unlikely, anthropogenic nitrogen sources, such as wastewater outfalls and leaking septic systems, may have significant local effects, especially during periods of low circulation.

Some inlets and subbasins are more susceptible to hypoxia because sills at the mouth of the subbasin slow mixing and increase residence time. Puget Sound has hypoxia hotspots including South Puget Sound, Hood Canal, and Quartermaster Harbor. However, hypoxia in these regions is largely driven by ocean-derived nitrogen and a reduction in flushing (reduced circulation, seasonally); although additional nutrients entering these regions from the land may exacerbate the problem (Khangaonkar et al. 2018). Studies done in the Strait of Georgia showed anthropogenic nitrogen inputs to be minimal (Sutton et al. 2013) with strong tidal mixing ameliorating low dissolved oxygen by mixing in oxygenated surface water (Ianson et al. 2016); both studies suggested that widespread eutrophication is unlikely. However, as in Puget

Sound, local anthropogenic activities, such as aquaculture and sewer outfalls, may produce enough additional anthropogenically-derived nutrients that short-lived local events may occur. In some locales and seasons, local hypoxia

may be exacerbated by larger-scale oxygen changes, such as the global deoxygenation and upwelling-driven low-oxygen ocean waters described above.

Hypoxia and Dead Zones

Hypoxia refers to low oxygen in aquatic ecosystems, usually a concentration of less than 2 or 3 milligrams of dissolved oxygen per liter of water (mg/L). Dissolved oxygen concentration is highly dependent upon temperature, but normal concentrations are typically 8 to 12 mg/L. A complete lack of oxygen (0 mg/L) is called anoxia. Typically, when waters become hypoxic, mobile organisms relocate to more favorable areas.

If the changes are sudden or widespread, the animals may become trapped and perish. Similarly, sessile (immobile) organisms are not able to escape hypoxic zones and will die if their oxygen demand exceeds the available oxygen. Areas where hypoxia is severe are called anoxic zones, sometimes referred to as “dead zones.” Often the only organisms alive in these anoxic dead zones are the ones that can live without oxygen (e.g., some microbes).



Waves crashing into wood debris, San Juan Island, WA
Photo: Ginny Broadhurst

Sea Level Rise

Globally, sea level has risen about 20 cm (7.9 in) on average over the past century, with average rates accelerating from 1.4 mm/yr (0.06 in/yr) until about 1970 to 3.6 mm/yr (0.14 in/yr) in the most recent period of observation from 2006 to 2015 (Intergovernmental Panel on Climate Change 2019). In the Salish Sea, sea level change has varied from -2 to 2 mm/yr (-0.07 to 0.07in/yr).

At most locations in the Salish Sea, sea level has risen over the same period, but a number of factors make rates of relative sea level rise variable (i.e., RSLR, represented by the rate of eustatic sea level rise combined with vertical land movement to result in the net change in height of the sea relative to land). Rates of sea level change vary depending on local land vertical motion, weather patterns, and ocean conditions, all of which may amplify or mute changes in sea level at local scales. Land movement can counteract or exacerbate rates of RSLR, depending upon which vertical direction the land is moving (Figure 4.11). For example, active tectonics are causing uplift of the land on the northwest tip of the Olympic Peninsula in Washington. Areas around Neah Bay in the Strait of Juan de Fuca are experiencing a relative decline in sea level of -1.8 cm/decade (-0.71 in/decade) for a total of about -13.2 cm (5.2 in) over the last 75 years due to uplift of the land exceeding the rise in eustatic sea level (the height of the water surface irrespective of the land; Mauger et al. 2015). In other areas in the Salish Sea, land is subsiding (downward movement of the land mass) due to sediment compaction, groundwater withdrawal, or erosion. Subsidence in conjunction with eustatic sea level rise leads to greater RSLR.

Much of the region is subsiding and most areas within the Salish Sea are seeing relative sea level rise. For example, Victoria has seen moderate increases in sea level (+9.1 cm or 3.6 in) over

the last 50 years (NOAA Tides and Currents Sea Level Trends 2017; Vadeboncoeur et al. 2016) while Seattle has experienced greater change, +24.7 cm (9.7 in) of RSLR since 1900 (NOAA Tides and Currents Sea Level Trends 2017; NOAA 2021). These measurements exemplify the local-scale variation in the region and stress the importance of accurate measurements of sea level to fully understand the impacts on developed land, infrastructure, and coastal habitats.

Global average sea level is projected to rise further, and at accelerating rates, with climate change, and the Salish Sea region is no exception. RSLR in the Salish Sea is expected to exceed 15 cm (5.91 in) by 2050 and 45 cm (17.7 in) by 2100 (Miller et al. 2018). When projecting relative sea level rise, several factors including global climate models, greenhouse gas scenarios, and estimates of the rate of vertical land motion all play a role in arriving at projections. As climate models are further refined, and as additional sea level monitoring and measurement data are collected, new projections are likely. Irrespective of predictions, sea level rise is not expected to rise in a consistent linear fashion, meaning relative slowing in RSLR may be temporary before an acceleration in RSLR that may have profound effects on low-lying coastal areas (Bromirski et al. 2011).

Increasing sea level will interact with tides, storm surges, and freshwater delivery from rivers leading to more frequent and more extreme coastal flooding. This will be especially apparent during extreme high tides, commonly known as king tides, which are normal (but very high and very low) tides that occur twice a year. If these high tides coincide with storms, water levels will increase even further. The Witness King Tides Project is using citizen science to collect

photographs of how king tides are impacting coastal resources (Witness the King Tides 2021). In Vancouver, BC, king tides overtop low-lying parts of a seawall that was designed based on sea level heights from the 1970s and 1980s. Sea level in Vancouver is expected to rise by as much as 50 cm (19.7 in) by mid-century, making the occurrences of flooding more likely.

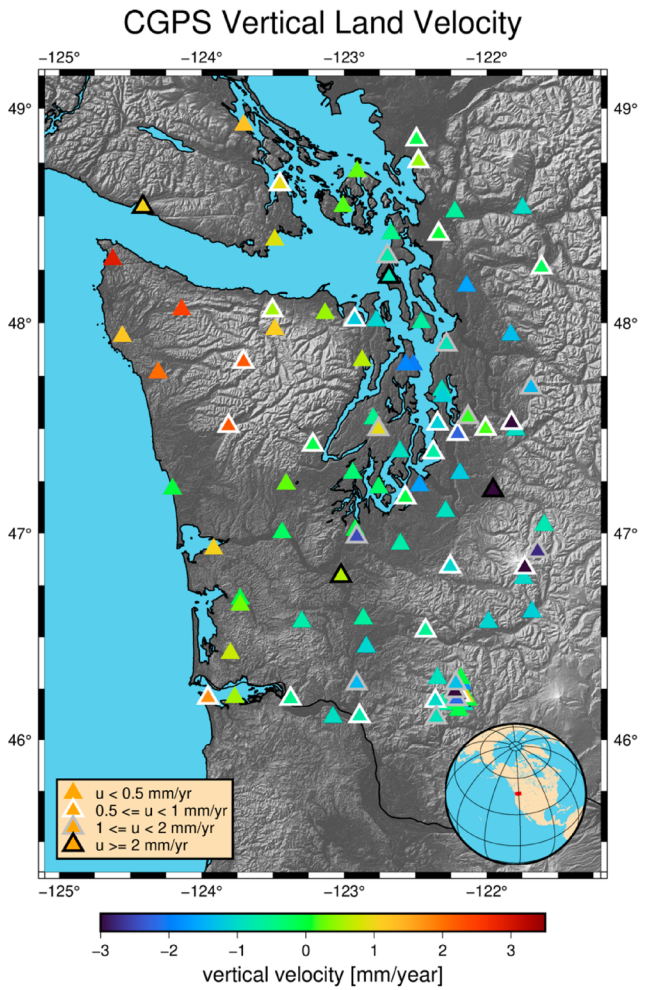


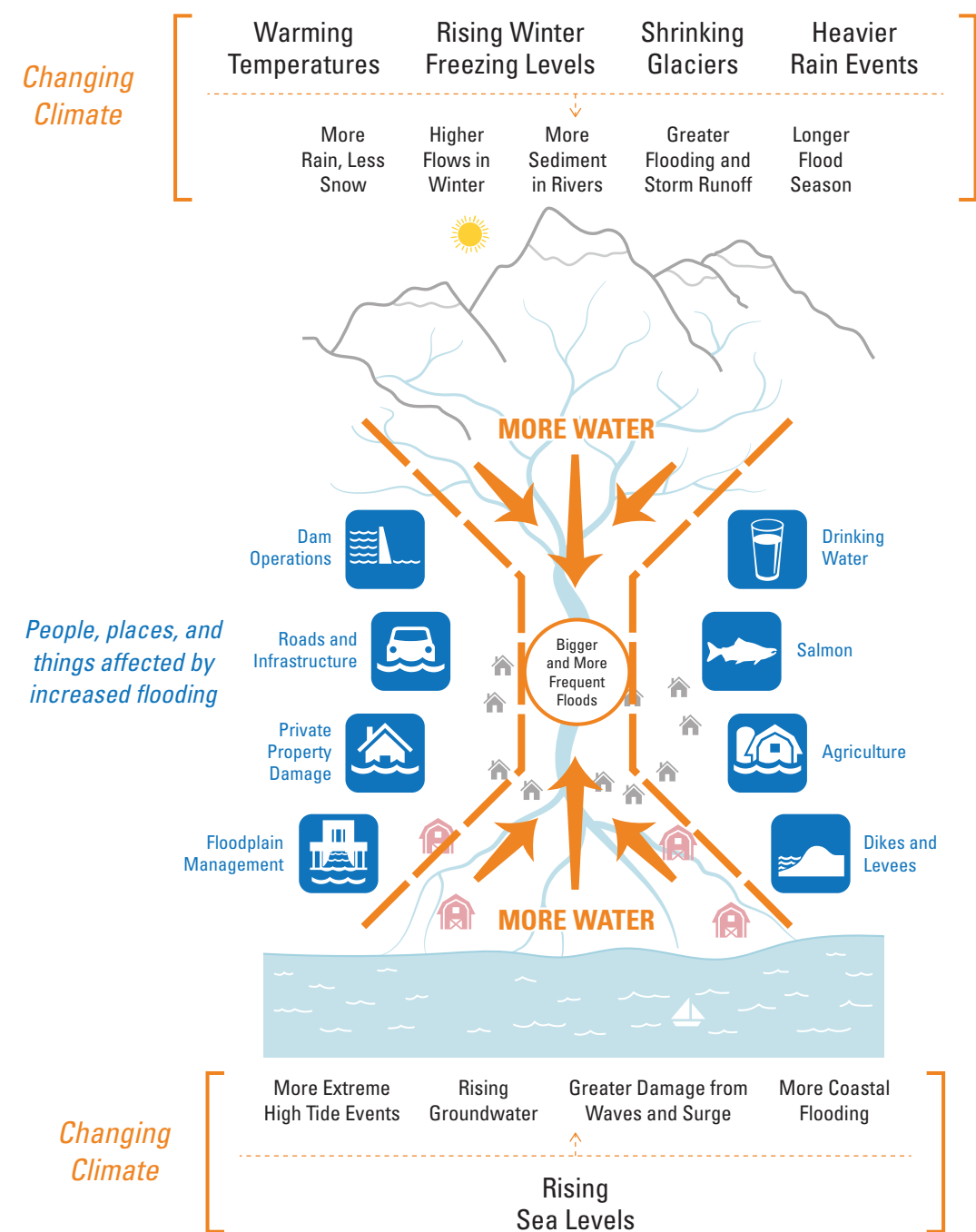
Figure 4.11. Relative rates of vertical land movement in the Salish Sea. Positive numbers and warm colors (red and orange) show uplift in land movement, while negative numbers (blue and teal) show subsidence. Areas with the greatest subsidence are likely to have the greatest impacts from relative sea level rise. Fine-scale understanding of land movement is important for predicting relative sea level rise locally. Source: adapted from Newton et al. (2021)

Sea level rise and storms are expected to threaten coastal development and critical habitat, such as low-lying estuaries, intertidal zones, and mudflats (Johannessen & Macdonald 2009). A higher sea level increases high-tide water levels and allows more wave energy to reach farther shoreward, enhancing the potential for coastal flooding and associated impacts (Bromirski et al. 2011; Figure 4.12). Inundation and erosion exacerbated by sea level rise are expected to cause habitat losses or shifts in habitat types, such as salt marshes, beaches, tide flats, eelgrass beds, and river deltas (see Vignette 15, Eelgrass Variations). Locations more likely to experience habitat loss include low-lying areas, locations with highly erodible sediments, and areas where inland migration of coastal habitats is hindered by bluffs or sea walls and other structures impeding sediment distribution (Mauger et al. 2015). Many of these locations are at the center of Indigenous communities, threatening personal and cultural property, as well as natural resources like shellfish beds (see Vignette 16, Climate Change Adaptation).

Sea level rise and the associated habitat changes in the marine environment are projected to also affect the geographical range, abundance, and diversity of Pacific Coast marine species and habitats, some of which use shallow water areas for rearing, although the extent to which this will be the case is still largely unknown. Shellfish and eelgrass beds are likely to change distribution with longer inundation times.

Climate Change: Combining Forces

Why Skagit Flood Risk is Increasing



Physical Impacts from Climate Change Occurring in the Salish Sea Ecosystem

A partial list of physical impacts occurring or projected for the Salish Sea ecosystem from changing climate is provided below. Both the [Climate Impacts Group](#) at the University of Washington and the [Pacific Climate Impacts Consortium](#) at the University of Victoria are leading extensive programs on actionable climate science in the region (Climate Impacts Group n.d.; Pacific Climate Impacts Consortium 2021).

- Warmer air temperatures
- Shrinking glaciers
- Less snowfall
- Decreasing summer streamflows
- Increasing winter peak flows
- Changes to timing of peak and base flows
- Higher freshwater temperatures
- Lower levels of dissolved oxygen in streams
- More sediment delivered into streams and ultimately to the Salish Sea nearshore
- Drying out of wetlands
- Regional drought
- Increased frequency and size of wildfires
- Greater probability of landslides
- Warmer ocean temperatures
- Rising sea levels
- Ocean deoxygenation
- Stronger storms and greater storm surge
- Changing ocean chemistry, including ocean acidification
- Changing, and slowed, currents

Figure 4.12. The intersection of climate change impacts. Increased freshwater flow will combine with rising sea level to result in increased coastal flooding and numerous secondary impacts. Source: Skagit Climate Science Consortium (2021)

ECOLOGICAL EVIDENCE OF CLIMATE CHANGE

Habitats, processes, and biota within the Salish Sea are showing evidence of climate change impacts, and this trend will continue. Research over the last two decades, combined with observations made during the marine heatwave in 2015-2016 and since, provide tangible evidence and useful insights into how local ecosystem structure, processes, and individual species are affected by climate change. The likely effects on other oceanographic, hydrologic, and biotic components are suggested by models, theory, and evidence from other regions and applied locally. Those emerging effects will become more apparent (and more fully documented) in coming years, especially as temperature, acidification, and other indicators

Phytoplankton

Although phytoplankton forms the base of the Salish Sea estuarine food web, there is much uncertainty about how phytoplankton production will change in the Salish Sea in response to climate change. In general, changes to phytoplankton dynamics may include changes to phytoplankton community composition (the species that dominate the phytoplankton), the timing of blooms (phenology), and abundance of species and communities. Projected changes in nutrient concentrations and light conditions, the limiting factors for primary production, as a result of climate change are thought to be minimal and are not anticipated to change primary production (Johannessen & Macdonald 2009). But primary production in the northern Salish Sea is linked to large-scale climate indices and

continue to increase to points that become stressful for native species and species that play a critical role in the food web. The examples discussed below are not intended to be an exhaustive cataloging of all climate change-related impacts in the Salish Sea, and in fact, while we suspect climate may be driving changes in some organisms and populations, evidence is still emerging and indirect effects are largely unknown (see Vignette 17, Salish Sea Jellyfish). But we briefly highlight several important ecosystem components for which climate-related impacts are documented as an entry-point for understanding biological response to climate change.

whether this relationship remains or shifts is of interest (Ji et al. 2010). In more southerly locations in the Strait of Georgia, local impacts of climate drive annual changes in primary production (Suchy et al. 2019); the same is thought to be true for Puget Sound, driven mostly by estuarine circulation. Comprehensive time-series on phytoplankton production do not exist, so evaluating recent trends is not possible. However, the mechanisms of change include increased temperature and CO₂, decreased pH and dissolved oxygen, and changes in timing and extent of freshwater input, which drives estuarine circulation and residence times.

Local variability in production is driven primarily by freshwater runoff, but also by winds and solar radiation, all of which affect water exchange,

air-sea gas exchange, mixing, and estuarine circulation (Riche et al. 2014). Together these processes provide the setting for primary production, and alteration could disrupt the annual onset and evolution of phytoplankton production. For example, the change in annual freshwater discharge (flattening of the hydrograph) from the Fraser River, the dominant freshwater source in the Salish Sea (Thomson 1981), may drive changes in timing of phytoplankton production (Johannessen & MacDonald 2009). Fraser River discharge is associated with circulation throughout the Salish Sea. With more of the discharge occurring in spring and less in summer, there may be an earlier spring bloom (Riche et al., 2014) and an overall change in primary production resulting from changes in circulation. Local inputs of nutrients might lead to increased production locally, and result in eutrophication in enclosed bays (Mackas & Harrison 1997).

Composition of the phytoplankton community is also subject to change, with climate change potentially bringing more frequent occurrences of harmful algal blooms (Johannessen & MacDonald 2009). Harmful algal blooms or HABs are occurrences of algal species that cause toxic effects or physical harm. For example, large blooms of spinose form algae can clog fish gills. In another example, certain algal species produce noxious and toxic substances

that can accumulate in food chains and cause illness or death in animals and humans. Mudie et al. (2002) suggested that observed increases in harmful algal blooms in the Strait of Georgia in the last several decades might have been caused by climate change. In a modeling study on *Alexandrium* spp. (a dinoflagellate), Moore et al. (2015) concluded that by 2050, global warming would lead to 30 more days a year with conditions favorable for *Alexandrium* blooms in Puget Sound. Additionally, suitable conditions for blooms could occur up to two months earlier and extend a month later (Moore et al. 2011). Warmer water in regional estuaries (e.g., South Puget Sound inlets) may contribute to a higher incidence of harmful blooms of algae linked to paralytic shellfish poisoning. These types of ecosystem impacts may then cause adverse economic impacts, such as beach closures affecting recreational or commercial harvesting of shellfish (Mote et al. 2014).

Changes to physical conditions that influence phytoplankton growth may also lead to an altered coupling between phytoplankton and zooplankton if bloom timing changes and zooplankton are slow to adapt. This type of change is very difficult to observe without high resolution data, and even when collected, it tends to be on a small spatial scale that limits inference, especially in a diverse ecosystem like the Salish Sea.

Kelp

In recent years, attention has turned to kelp and the ecological role it plays in the Salish Sea ecosystem. While stressors related to land-use induced changes to the seascape (e.g., overwater structures) have reduced growing habitat for kelp, increases in air and water temperature associated with climate change are of particular concern for Salish Sea kelp species. Growth has been correlated with sea surface temperature, where higher temperatures produce lower growth and poor recruitment (Pfister et al., 2018). Intertidal kelps may be especially susceptible to rising air temperature, which can lead to more rapid desiccation and inability to withstand the ambient temperatures on a given tide cycle.

Research in Barkley Sound, BC (outside the Salish Sea along the west coast of Vancouver Island), may be indicative of what kelp experience within the Salish Sea: species loss, declines in kelp cover, and declines in recruitment coinciding with warm temperatures (Starko et al. 2019). This study showed kelp in inlets with low wave exposure, restricted circulation, and warmer temperatures to be especially hard hit by the 2014 to 2016 warming event. Emerging data from Puget Sound also show declines in kelp cover to be most pronounced in inlets in South Puget

Sound where circulation is restricted and temperatures are elevated (Berry et al. 2021).

In some cases, climate change may lead to positive responses from organisms. As photosynthetic organisms reliant on CO₂ but living in a generally low-CO₂ environment, kelp and eelgrass may benefit. Increased CO₂ has been experimentally shown to increase the net primary production in eelgrass and kelp (Thom 2005; Palacios & Zimmerman 2007). In another study, satellite data showed the kelp, *Nereocystis luetkeana*, to be resistant to the heat wave on the Oregon coast (Hamilton et al., 2020).

As these examples help illustrate, changes in distribution and abundance of biogenic habitats like eelgrass and kelp will be driven by local change, global change, and the intersection of the two at discrete spatial and temporal scales. Fluctuation in kelp abundance has been linked to both broad-scale oceanic conditions, as indicated by the Pacific Decadal Oscillation and North Pacific Gyre Oscillation, and to local-scale impacts on water quality, temperature, and increased herbivory (Taylor & Schiel 2005; Foster & Schiel 2010; Burt et al. 2018; Pfister et al. 2018; Schroeder et al. 2020), illustrating that failure to account for the local or global scale could dramatically change inferences about populations.

Coastal Wetlands

Coastal ecosystems are already impacted by the combination of climate-related ocean changes and adverse effects from human activities. Sea level rise will continue to have profound impacts on coastal wetlands, including salt marshes, freshwater marshes, forested swamps, and seagrass beds. These are valuable ecosystems, providing habitat for invertebrates, fishes, and birds and contributing a range of ecosystem services related to coastal protection. Coastal wetlands store carbon in aboveground and belowground biomass, and are important for buffering stormwater, filtering excess nutrients and other contaminants, and absorbing floodwaters during periods of high precipitation and runoff.

Much of the region’s coastal wetland habitat has been lost due to urbanization (85% of historical area along the United States West Coast; Brophy et al. 2019), sharply reducing coastal protection and habitat provisioning. A recent study showed that within moderate sea level rise scenarios, most coastal wetlands will be reduced in size or lost by the end of the century (Thorne et al. 2018). Wetland response to sea level rise is a function of available sediment supply and adequate hydrodynamics to maintain marsh height. Some coastal wetlands will decline in quality as periods of inundation lengthen.

The intersection of urbanization and climate change is especially detrimental for low-lying coastal areas. Many coastal wetlands, tide flats, and beaches will decline in extent as a result of sea level rise, particularly where coastal wetlands cannot adapt by shifting inland due to geography or infrastructure such as roads and ports. These physical constraints are known as “coastal squeeze.” In some cases, marshes will be able to migrate landward, but many regions will

experience coastal squeeze because extensive coastal development limits the extent to which marshes can migrate and adapt. Species such as shorebirds and juvenile salmon could be impacted by further loss of this already limited habitat.

The communities most likely to be impacted by rising sea level and the resulting loss of coastal wetlands include many Tribal and First Nations communities who have lived along the shores of the Salish Sea for thousands of years. Settlement trends, first by Indigenous peoples and later by European settlers, have played an important role in increasing low-lying coastal communities’ exposure and vulnerability to sea level rise and extreme sea rise events (Pörtner et al. 2019). The attributes that made settlement locations desirable at the outset (e.g., proximity to waterways and harvest sites) are their very vulnerability. Loss of shellfish habitat, inundation of dwellings and infrastructure, and increased coastal erosion on Indigenous lands are just some of the impacts already affecting Indigenous communities in the Salish Sea (Northwest Indian Fisheries Commission 2016; Vadeboncoeur et al. 2016). Salmon fisheries have long played an important role in Tribal and First Nations communities by supporting cultural activities and providing food security. Loss of rearing habitat in coastal wetlands will further compromise the sustainability of already stressed salmon runs, and increasing inundation will threaten shellfish resources as well. Tribes are considering the ability of coastal wetlands to adapt or maintain resilience to sea level rise as part of their climate mitigation plans (Northwest Indian Fish Commission 2017; Ramirez & Simenstad 2018; Swinomish Indian Tribal Community 2010), but the ability to respond is compromised by existing development.

Salmon

Pacific salmon are intimately linked with the identity of Coast Salish peoples and are more broadly identified as an icon of the Pacific Northwest. In their assessment of Pacific salmon vulnerability to climate change, Crozier et al. (2019) identify a number of climate-related factors threatening the existence of Pacific salmon in the Salish Sea and beyond. These factors include: increasing stream temperatures that influence rearing duration and adult holding and upstream migration timing; summer water deficits that limit upstream migration; increased streamflow variability and flooding that could scour redds and increase egg mortality (Ward et al. 2015; Weinheimer et al. 2017); increased ocean acidification that impacts the salmon sensory system directly (Williams et al. 2019) and food resources (Busch et al. 2013); and changing ocean conditions that impact what can be a lengthy ocean residency of several years for some species and life history types (Crozier et al. 2021; Sobocinski et al. 2021).

Adaptive capacity within salmon populations, including the life-history diversity that allows for adaptation as conditions change, could help mitigate climate impacts. In an analysis of Fraser River sockeye, an important component of salmon biomass in the Salish Sea, Reed et al. (2011) found that evolutionary adaptation may be more rapid than the rate of climate change, allowing sockeye to change their migratory behavior as they have in the Columbia River (Beechie et al. 2006; Crozier et al. 2011).

In much of the region, the expression of life history diversity in migratory behavior and habitat

use has been reduced from historical levels (Burke 2005). For example, where protracted outmigrations once meant salmon migration downstream and into the saltwater from late winter through fall, we now see pulses of homogeneous, transient, and predominantly hatchery fish migrating in a more constricted period of May to July (Rice et al. 2011; Greene et al. 2021). The repercussions to wild populations from hatchery practices are a topic of ongoing research (e.g., density-dependence in habitat-limited estuaries). Additionally, a recent evaluation has shown implications of hatchery practices on predation that may be detrimental to wild stocks in the marine waters (Nelson et al. 2019).

In the vulnerability assessment, Puget Sound stocks were considered less vulnerable than others along the Pacific Coast due to their life-history diversity, extensive use of multiple habitats types, and shorter freshwater migrations (less time in warming rivers) than other populations (Crozier et al. 2019). But coho and Chinook salmon and steelhead trout all show high sensitivity and exposure to the metrics assessed and all three species have shown population declines (Sobocinski et al. 2018). Furthermore, there has been an overall decline in marine survival over the last 40 years (Zimmerman et al. 2015; Kendall et al. 2017; Ruff et al. 2017) to levels so low that additional mortality could be devastating to populations. The marine ecosystem is projected to continue to undergo major changes, with potentially significant consequences for Pacific salmon in the years to come (see case study on salmon marine survival).

Marine Birds

There are over 170 species of birds that rely on the Salish Sea for foraging, rearing, or nesting (Gaydos & Pearson 2011). Birds integrate across the seascape by using different habitats throughout their life cycle and within any single feeding or rearing season. Shorebirds, like sandpipers (*Calidris mauri*), may stop on tidal flats rich with invertebrates and marine biofilm (a thin layer of microbes and benthic diatoms on the surface of mudflats) as a stopover prior to nesting (Schnurr et al. 2020). Other birds, like surf scoters (*Melanitta perspicillata*) rely on herring spawn found on eelgrass and algae (Lok et al. 2012). Nesting on islands or in Salish Sea watersheds and foraging in the marine waters and on tideflats means birds, like salmon, rely on multiple intact and productive habitats for survival as individuals, populations, and communities.

Since the 1990s, the abundance of wintering marine birds has been declining, with birds dependent upon forage fishes as prey (especially those that dive for their food) experiencing the most severe declines (Vilchis et al. 2015). Recent work from Canada showed downward trends in abundances for many bird species within the Salish Sea, but stable trends in those same species from the Pacific Coast (Ethier et al. 2020). These species were primarily piscivores (those that rely on fish prey), but marbled murrelets (a bird that relies on both fish and microzooplankton prey) has also shown evidence of prey limitation (Norris et al. 2007). Forage fish abundances in the Salish Sea have varied in recent years, are currently below historical levels, and are also thought to be sensitive

to environmental change (see case study on Pacific herring). If the current distribution and abundance of sandlance, surf smelt, and herring is driven by environmental change, there may be an indirect climate effect for birds if the prey abundances are low enough to impede productive foraging for marine birds, an activity that is regulated by metabolic costs. The loss of forage fish spawning habitats as nearshore conditions degrade may be driving low forage fish abundances (Vilchis et al. 2015), although in many cases the fish are not habitat limited. Pollution and disturbance are other potential causes of seabird decline.

Any climate impacts are likely compounded by other anthropogenic effects, especially given the differential trends from animals primarily foraging within the Salish Sea and those outside (Ethier et al. 2020). This same differential mortality has been observed in salmon (see case study on Pacific salmon marine survival) and underscores the need to better quantify the impacts of human presence and activity on biota. Climate impacts are likely to be both direct and indirect and will be difficult to isolate from other existing stressors. Ecosystem integrators like seabirds (e.g., scoters, loons, mergansers, and gulls) and Pacific salmon—species that move across the landscape and seascape—are important sentinels of ecosystem change, thus sea bird monitoring (e.g., Norris et al. 2007) could provide an indication of functional ecosystem changes resulting from landscape (Allen et al. 2019) and seascape change (Diamond & Devlin 2003; Vilchis et al. 2015).

SUMMARY OF CLIMATE CHANGE IN THE SALISH SEA

Evidence for human influence on the climate system has grown since the first assessment report was presented by the Intergovernmental Panel on Climate Change in 1990. Growing populations and fossil fuel-based economies around the world are responsible for increasing greenhouse gas emissions, driving large increases in the atmospheric concentrations of CO₂, CH₄, and N₂O. About half of the cumulative anthropogenic CO₂ emissions between 1750 and 2011 have occurred in the last 40 years (high confidence; Intergovernmental Panel on Climate Change 2014) and the global ocean has absorbed about 30% of the emitted anthropogenic CO₂ since the industrial era began (Pörtner et al. 2019). In these recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. This human influence is evident in warming of the atmosphere and the ocean, in changes in the global water cycle, and in global mean sea level rise—all effects contributing to changes within the Salish Sea ecosystem. While the Salish Sea is nested within the larger Earth system where these global-scale changes are occurring, the rapid pace of local population growth, urbanization, and associated carbon emissions have direct impacts on the Salish Sea and contribute to climate change both globally and locally.

While the causes of climate change are global and primarily from greenhouse gas emissions, impacts of climate change manifest locally. The Salish Sea and its physical and biological components are already experiencing some of the effects of global climate change, including changing precipitation regimes, increasing sea water temperatures, and ocean acidification. Scientists are beginning to understand some of the predicted near-term effects of global climate

change from climate models that continue to improve in their accuracy and applicability at the regional scale. However, what's lagging behind is our understanding of how organisms, ecosystem processes, and interactions are affected by global climate change today and more so into the future. Combined with increasing disruption from local human impacts, the dynamics of the Salish Sea estuarine ecosystem will undoubtedly change, and making predictions about these changes will remain a challenge.

This section of the *State of the Salish Sea* report has provided a snapshot of the many physical factors driving climate change impacts in the Salish Sea. Each of the projected impacts has associated uncertainty, but climate models and empirical observations from recent years provide confidence in the general trends seen to date and expected in the future within the Salish Sea ecosystem. What is less certain is the biological response and response of complex ecosystem processes like food web dynamics, energy and nutrient cycling, and biomass production. Changes in many of these biophysical processes are not easily detected due to a high degree of natural variability.

Complex processes often exhibit nonlinear dynamics, hysteresis (a lag in response before reaching a tipping point; Selkoe et al. 2015) and potentially a new stable state (Carpenter et al. 2000; de Young et al. 2008). Many have suggested the Salish Sea, and the North Pacific Ocean more broadly, experienced a regime shift in the late 1980s related to changing global climate (Benson & Trites 2002; Hare & Mantua 2000; Möllmann & Diekmann 2012; Perry & Masson 2013). Since that time, a growing body of scientific and anecdotal evidence suggests structural changes within the Salish Sea are driving changes in species distribution and

abundances, from benthic invertebrates (Partridge et al. 2018) to groundfish (Essington et al. 2021), although time-series for many organisms do not exist. Continued monitoring and assessment is the only way to capture natural variability and discriminate signals from perturbations.

There is growing evidence from around the world that an organism's sensitivity, as well as exposure, drive that organism's vulnerability to climate change and realized ecosystem changes (Hare et al. 2016; Jones et al. 2018; Hughes et al. 2019). It's important to keep in mind that the rate of change in the system and an organism's ability to adapt, known as adaptive capacity, may be as important in determining long-range outcomes as the magnitude of the change itself. Indeed, some species may be climate "winners" and thrive on a warming planet. For example, species that are at the northern extent of their range in the Salish Sea may benefit as sea water warms and the center of their distribution moves north (Pinsky et al. 2013; Morley et al. 2018). Many of the organisms in the Salish Sea are found within the larger California Current ecosystem and are not at the southern (warmest) extent of their range within the Salish Sea. In contrast, some species may be climate "losers" and not have sufficient adaptive capacity to keep up with the rate and type of changes underway. An example is Pacific Cod (*Gadus macrocephalus*), which was once common in the Salish Sea. Today they are found in lower abundances than in the past and may be extirpated from the region with warming water temperature.

Given the nonlinear dynamics of change, the lags from hysteresis, and our inability in some cases to clearly identify key trends and thresholds, early detection of significant changes is a challenge. Changes in multiple species taken collectively

can lead to asynchrony in species interactions and disrupt the entire ecological community (Sydeman & Bograd 2009). Both iconic species and those lesser known in the Salish Sea will continue to be affected by changes in physical conditions in the Pacific Ocean, changes in watershed hydrology and freshwater input, and increases in temperature, sea level, and ocean acidification (Burkett et al. 2005; Hewitt et al. 2016; Samhoury et al. 2017). To improve our ability to detect these changes early and quickly develop adaptive management strategies, a combination of experimental work and modeling with forecasting capabilities based on strong observational data collection efforts, will be needed. Combined with "rapid-response" type studies during natural experiments, these will be the best tools for understanding how climate change is impacting the Salish Sea ecosystem and its associated human systems.

In addition to ecosystem changes, we cannot ignore that there are also economic and cultural consequences for human communities (Adger 2010), many of which will not be equitably distributed (Islam & Winkel 2017). Some of these consequences are related to sea level rise, land and habitat loss, and changing distributions of organisms that people in this region have relied upon for generations (Lynn et al. 2014; Marushka et al. 2019). Our ability to respond to the inevitability of climate change will be somewhat dependent upon the resilience of the ecosystem and its ability to adapt, but also on our own individual and collective will to reduce the local impacts and perturbations that will potentially compound the globally driven change.

12 | THE BLOB: WHAT WERE ITS IMPACTS ON THE SALISH SEA?

Dr. Nicholas Bond, Cooperative Institute for Climate, Ocean and Ecosystem Studies, University of Washington

A marine heat wave (MHW) of unprecedented severity, areal extent and duration occurred in the Northeast Pacific Ocean during 2014-2016. This event, known as the “Blob”, had a wide variety of far-ranging effects on physical, chemical, and biological ocean properties; here we focus on the Salish Sea. The Salish Sea is connected to the open ocean, of course, and so it stands to reason that the Blob must have influenced our local waters. However, it is not necessarily obvious how, and to what extent. Because the Blob was such a massive perturbation, it represents an attractively large signal for inquiry. Conceivably it represents a dress rehearsal for typical conditions in future decades due to global climate change. With those ideas in mind, the purpose of this piece is to briefly review what happened and the lessons learned.

The near surface waters of the Northeast Pacific began warming substantially, relative to seasonal norms, in the winter of 2013-2014. This warming, which actually entailed less seasonal cooling than usual, can be attributed to a persistent ridge of higher than normal pressure that set up shop over the Gulf of Alaska. The ridge disrupted the usual parade of storms that cross the Northeast Pacific that time of year, with lower wind speeds as a result. The consequence was less heat drawn out of the upper ocean (one cools off a bowl of soup by blowing on it) and suppressed mixing of colder water from below, and ultimately surface temperatures that were as much as 2-3°C on the warm side by early spring 2014 over a large area offshore of the Pacific Northwest. Once formed, this mass of warm water was maintained by an overall reduction in low cloud coverage, and hence enhanced solar heating, in the warm seasons of 2014 through 2016. It was also reinforced by a weather pattern in the winter of 2014-2015 that featured anomalous winds from the south,

of sub-tropical origin, and a shift in the overall pattern to include positive sea surface temperature (SST) anomalies along the coast of western North America (Figure 1). For the most part, the Blob ended in late fall of 2016, in association with an active storm track that brought a preponderance of cool winds out of the northwest. On the other hand, a lingering hangover from the Blob was still noticeable through 2019 at depths roughly between 100 to 300 meters, particularly in the Gulf of Alaska.

The Blob both directly and indirectly impacted the Salish Sea. The Salish Sea’s primary exchange with the open ocean is at the west entrance of the Strait of Juan de Fuca; ocean conditions at that location both impact the properties of the inland waters and modulate their ventilation (i.e., residence times). The Northeast Pacific also indirectly influences the Salish Sea through its effects on the weather. Because the prevailing winds usually include an onshore-directed component, sea surface temperature anomalies off the coast of the Pacific Northwest tend to be reflected in air temperature anomalies of the same sense. The record high temperatures in Washington State during the winter of 2014-2015 can be attributed in part due to the Blob.

With that lead-in, let us now consider what happened in the Salish Sea. Much of the following information is cribbed from the “Puget Sound Marine Waters” annual overviews produced by the National Oceanic and Atmospheric Administration’s (NOAA) Northwest Fisheries Science Center for the Puget Sound Ecosystem Monitoring Program’s Marine Waters Workgroup, and interested readers are encouraged to check out those overviews.

The Blob really began rearing its ugly head in fall 2014 when the seasonal transition in the coastal

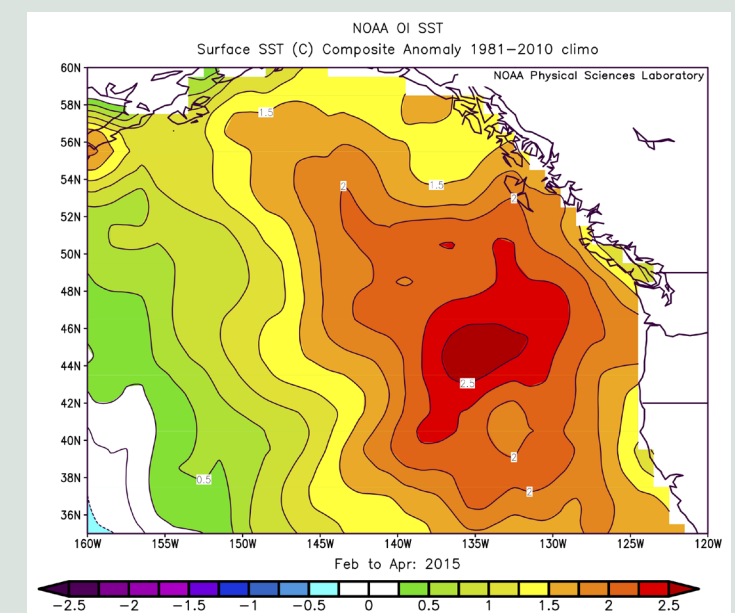
winds from upwelling to downwelling shoved the extremely warm water lurking offshore right up to the coast. The warm water entering the Strait of Juan de Fuca at that time meant that the density differences driving the estuarine circulation were weakened. An important consequence of the lack of flushing was abnormally low oxygen concentrations in some locations, especially in lower Hood Canal. The relatively warm and sunny weather during fall 2014 was accompanied by a prominent phytoplankton bloom.

The heyday of the Blob was during 2015. The aforementioned warm winter of 2014-2015 resulted in the most paltry snowpack for the Pacific Northwest in the historical record. Because the precipitation was much more in the form of rain rather than snow, there was greater freshwater runoff than usual in early 2015, leading to low salinities in the upper part of the water column, and very low streamflows in summer 2015, resulting in high salinities. The latter had the positive effect of promoting vertical mixing, and hence helped in some locations to keep oxygen concentrations at depth from cratering. That being said, the open ocean conditions associated with the Blob imply that there were relatively long residence times for the waters of the Salish Sea with a host of incompletely known consequences. This was a year that will long be remembered for harmful algal blooms of *Pseudo-nitzschia* spp. along the west coast of North America, but the Salish Sea also got in the act with an amazingly early bloom of *Alexandrium* spp. in Hood Canal in April and numerous examples of *Vibrio*-contaminated oysters. Impacts on higher trophic levels also became apparent, including herring, seabirds (e.g., rhinoceros auklets) and some species of marine mammals.

The year of 2016 was less extreme as the Blob wound down, but the Salish Sea definitely remained on the warm side. This year also featured a continuation of the recent trend for warmer spring weather and rapid snowmelt, with the result being earlier freshening of the near-surface waters of the Salish Sea. Herring populations and some seabird and marine mammal species continued to struggle.

The post-blob period of 2017-2019 represents a mixed bag. The return of more normal conditions—whatever that means during a time of inexorable trends in physical and chemical ocean properties—was accompanied by recovery in some populations and continued declines in others. A telling example here is the plight of the southern resident orcas, who apparently spent relatively little time in the summer of 2019 in their usual haunts in the Salish Sea, perhaps because of the Blob’s longer-lasting impacts on Chinook salmon runs.

In terms of takeaways, perhaps the Blob can serve as a wake-up call. The climate community appreciated the overall warming that was occurring, but still was stunned by the magnitude of this recent event. The marine ecosystem response was complex, especially at higher trophic levels, and it is proving to be no cinch to tease out the interplay between all the potential factors. Better understanding of the Salish Sea’s response to the climate forcing through improved monitoring and further research is necessary. We know that the Salish Sea will experience future events, and that they are liable to be even more extreme and with profound effects, given the background warming and changing ocean chemistry.



Sea surface temperature (SST) anomaly distribution (°C) for February-April 2015 from NOAA’s Optimal Interpolation Sea Surface Temperature dataset. Source: NOAA/ESRL Physical Sciences Laboratory from their website at <http://psl.noaa.gov/>.

13 THE SALISH SEA MODEL – FOR DIAGNOSTIC BIOPHYSICAL ASSESSMENTS SUPPORTING ECOSYSTEM RESTORATION AND WATER QUALITY MANAGEMENT

Dr. Tarang Khangaonkar, P.E., Salish Sea Modeling Center, University of Washington, Tacoma, and Pacific Northwest National Laboratory

“Why is there persistent annual occurrence of hypoxia in Hood Canal but not in Saratoga Passage? Why does Padilla Bay support a healthy eelgrass meadow while Skagit Bay and Port Susan appear to be losing vegetation? Why do we continue to detect PCBs in fish tissue and the food web despite many years of source control and sediment remediation efforts? Will nutrient reduction strategies be effective in managing dissolved oxygen near algal blooms? And will they also provide ocean acidification relief? What do we know about the operation of net-pens and potential spreading of released particulate matter and disease, and how does Salish Sea circulation and transport affect accumulation of microplastics and marine debris?”

These are examples of some of the leading questions currently being addressed by our water quality management and regulatory agencies. Given numerous concerns related to the health of the ecosystem and the possibility of anthropogenic impacts—from population growth to climate impacts, such as sea level rise—scientists, engineers, and planners seek an improved basic understanding of the biophysical behavior of the Salish Sea. The Salish Sea Model (SSM) development was motivated by this urgent need for a comprehensive predictive model that could diagnose water quality issues and concerns and serve as a planning tool in support of Puget Sound restoration efforts. The model framework and formulation were selected specifically to allow assessments of concerns, such as recurring hypoxia in Puget Sound, loss of eelgrass meadows,

loss of nearshore habitat, and persistence of toxic contaminants in sediments and tissue. The SSM was developed by the Pacific Northwest National Laboratory in collaboration with the Washington State Department of Ecology (Ecology) and with support from the United States Environmental Protection Agency (USEPA) (Khangaonkar et al. 2018).

The SSM was designed to function at an academic/scientific research level of quality, but with practical applications and use by the broad Salish Sea community in mind. It uses an unstructured approach in which the model domain is represented by a grid/mesh made up of triangular cells over which Navier-Stokes equations of continuity and momentum are solved. This provides flexibility, encompassing regions with complex shorelines and the presence of multiple islands. The approach also allows the model resolution to be refined locally for site-specific applications. Right from early-developmental stages, SSM sub-domains with the finite volume community ocean model (FVCOM) framework have been deployed in support of feasibility analyses for nearshore restoration projects. Despite best intentions, efforts to restore nearshore habitats can result in poor outcomes if water circulation and transport are not properly addressed. Land use constraints can lead to selection of suboptimal restoration alternatives that may result in undesirable consequences, such as flooding, deterioration of water quality, and erosion, that require immediate remedies and costly repairs. Quantitative models designed for application to the nearshore

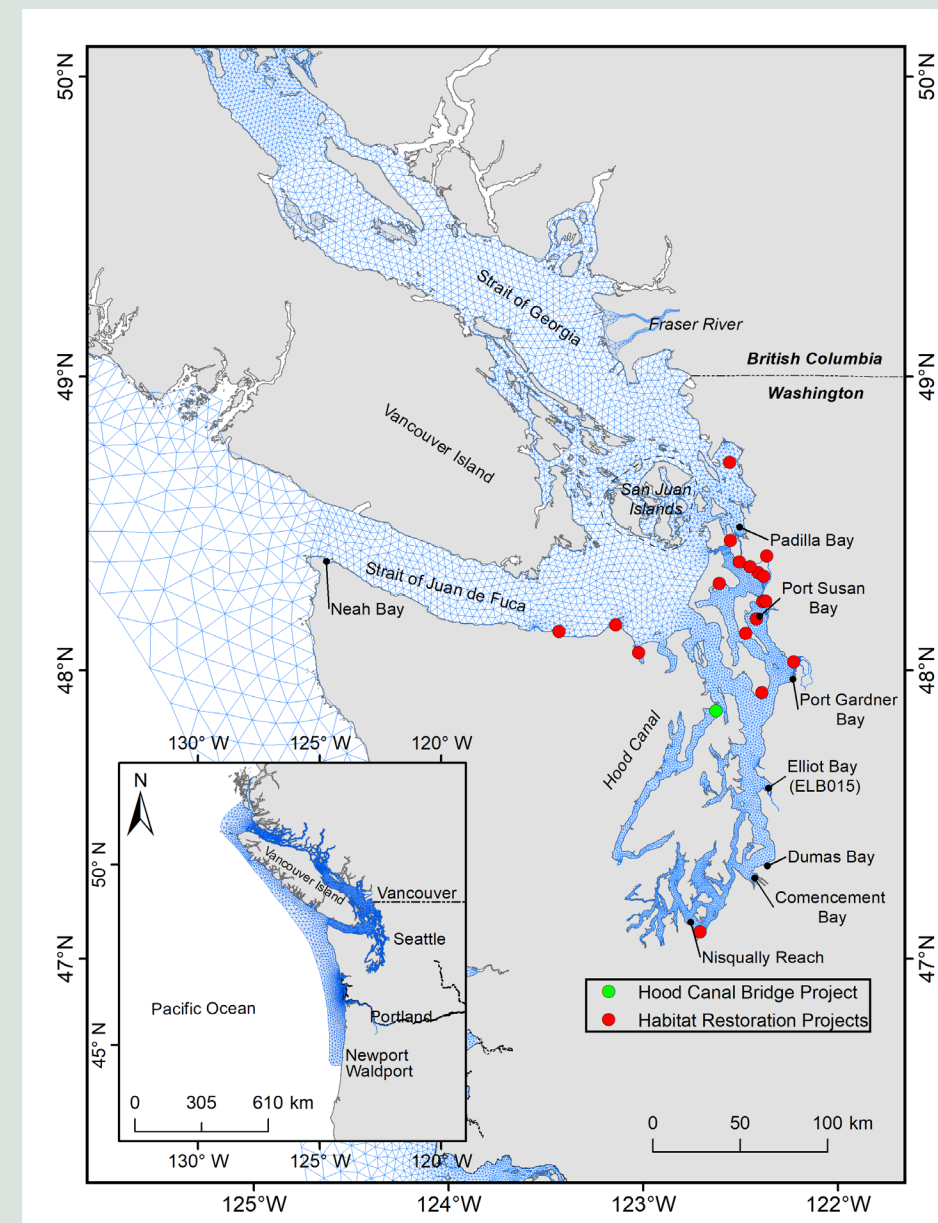


Figure 1: Project sites in the Salish Sea where site-specific applications of FVCOM based hydrodynamic models were developed as part of restoration feasibility or environmental assessment and design efforts. These applications included stand-alone as well high-resolution sub-basin applications embedded within SSM. Source: Tarang Khangaonkar

environment can minimize uncertainty about restoration goals, such as recovery of tidal exchange, supply of sediment and nutrients, and establishment of fish migration pathways. Starting with one of the earliest and largest restoration efforts in Puget Sound (Nisqually National Wildlife Refuge) to recent projects in the Whidbey Basin, the model has provided hydrodynamic simulations in the intertidal nearshore environment, predicting cumulative effects of multiple dike-removal, dike breach, and dike-setback scenarios on tidal currents, inundation frequency, connectivity, and sedimentation and

erosion processes. Figure 1 shows locations of various sites in the Salish Sea where SSM was used with high resolution ($\approx 10\text{--}25\text{ m}$) in sub-basins of interest, either in stand-alone (cut-out) mode or embedded within SSM as part of restoration feasibility or impact assessments prior to project implementation.

The familiarity with the Salish Sea environment and years of on-water experience sometimes convinces us of potential remedial actions based on intuition, personal convictions, and desired expectations. However, this inland fjord is complex, and the nearshore intertidal reaches where most development activity and anthropogenic impacts first occur—with tidal ranges greater than 3 meters over most of the domain—are too complex and challenging to rely on scaling inferences and past project experiences alone. For example, having recognized that the anthropogenic nutrient loads to the Hood Canal basins were relatively small, many of us were convinced that hypoxia in Hood Canal was somehow tied to the Hood Canal floating bridge.

The hypothesis was that bridge presence directly obstructed surface currents and therefore likely impacted large-scale circulation and flushing (Khangaonkar & Wang 2013). Application of the SSM as part of the Hood Canal Bridge Impact Assessment showed that the floating bridge indeed creates a zone of influence which affects currents, salinity, and temperature patterns in the near field (3–6 km; Khangaonkar et al. 2019). However, it also demonstrated that the original intuitive conviction that the bridge contributes to hypoxia in the Lynch Cove region of Hood Canal approximately

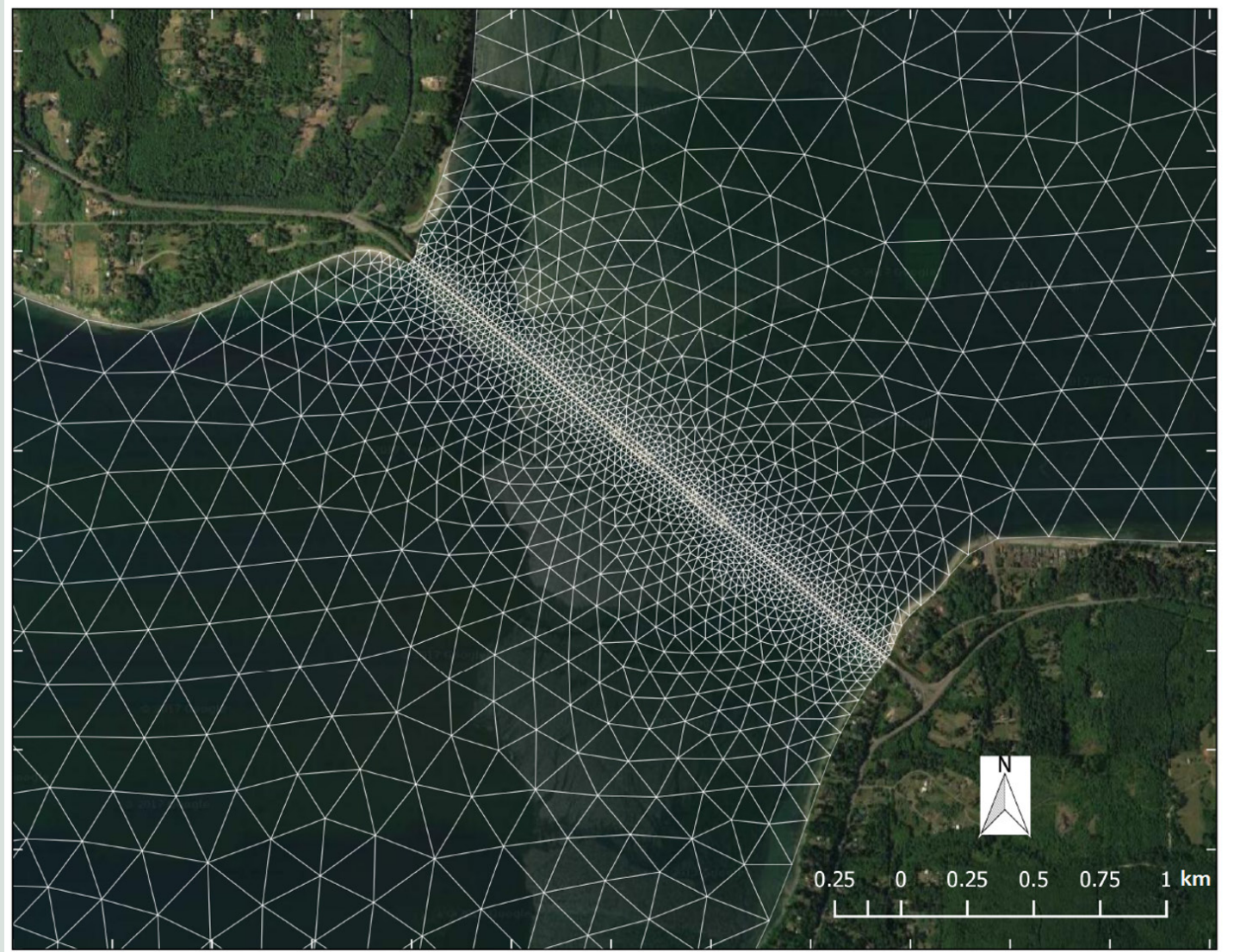


Figure 2. Salish Sea Model grid with refinement near the Hood Canal Bridge region to facilitate incorporation of the bridge block effects on circulation and water quality (biogeochemistry).

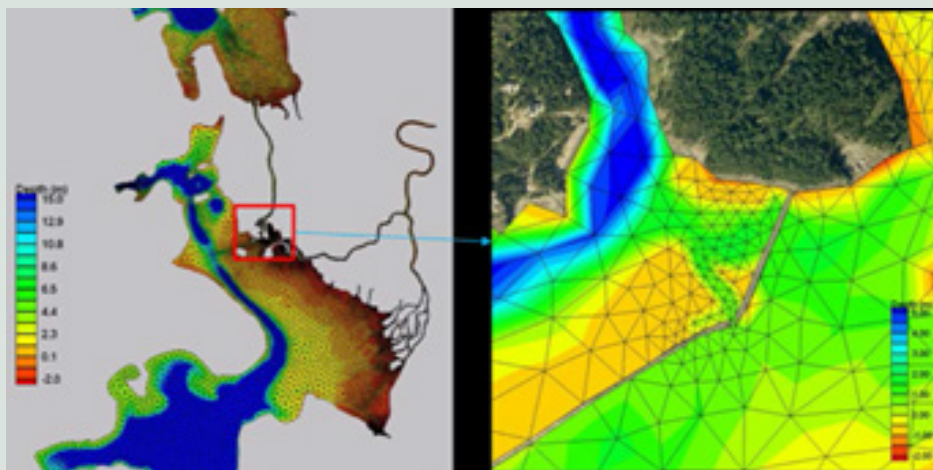


Figure 3. A closeup of model grid near McGlinn Island jetty near the mouth of North Fork Skagit River.

80 kilometers away was likely incorrect. The magnitude of hypoxia and overall basin flushing time appeared to be unaffected by the presence of the bridge based on numerous model tests. However, the SSM-based modeling effort did show that the hypoxia magnitude (exposure in area-days) was instead directly affected by overall nutrient pollution entering the Salish Sea and the resulting increase in algal growth. In other words, improvement to Hood Canal

hypoxia will require overall improvement in Salish Sea water quality and cannot be addressed by Hood Canal sub-basin focused actions alone. Figure 2 shows a SSM grid with site-specific refinement down to 18-meter scale for embedded simulation of the Hood Canal Bridge block along with the rest of the domain.

This ability of SSM to conduct high resolution applications with shoreline structures has proven particularly useful in providing information to decision makers in situations where ecosystem goals may conflict with regional infrastructure needs. For example, the 16-kilometer Swinomish Federal Navigation Channel, which provides navigation access to Northern Puget Sound by connecting Skagit and Padilla Bays requires periodic maintenance dredging and dikes to train Skagit River flow and sediments away from the channel.

The Swinomish Channel is in need of repairs to dikes/jetties, as sedimentation has increased, but the wear and tear and resulting breaches are seen as beneficial to migrating fish. The proposed repairs and dike constriction actions for channel maintenance appear to be in conflict with salmon habitat restoration goals aimed at improving access, connectivity, and brackish water habitat. The model was applied to assess the feasibility of achieving the desired dual outcome of (a) reducing sedimentation and shoaling in the Swinomish Channel and (b) providing a direct migration pathway and improved conveyance of freshwater. Figure 3 shows a closeup of model grid refinement and application to evaluate impacts on sediment deposition and salinity patterns. The results showed that connectivity and the desired brackish environment could be restored effectively through one of the scenarios considered but would come at increased dredging and maintenance costs (Khangaonkar et al. 2017).

For the scientific and the regulatory community in the Salish Sea, a key performance measure for acceptance of biogeochemical models has always been their ability to reproduce nutrient-algae annual cycles and dissolved oxygen (DO) levels. DO is often regarded as an indicator of water quality, and the

ability of the model to reproduce recurring hypoxia in sub-basins, such as Lynch Cove, Penn Cove, and East Sound, and responsiveness to anthropogenic nutrient loads from watershed runoff and wastewater loads is desired. This elusive goal had stymied ecosystem modeling research and nutrient management efforts in the region for decades. The SSM has successfully reproduced estuarine circulation, inter-basin exchanges, and annual biogeochemical cycles in the inner waters of Puget Sound, Georgia Basin, the San Juan Islands, and the Northwest Straits. SSM-based results have shown that nutrient loads from land-based sources are responsible for approximately 62% of exposure to hypoxic waters in the Salish Sea (Khangaonkar et al. 2018). The model has since been selected as the tool of choice by the USEPA and Ecology for developing the Marine Water Quality Implementation Strategy (MWQ IS) and is currently supporting the Puget Sound Nutrient Source Reduction Project (Ahmed et al. 2019).

In recent years, several new capabilities have been added to SSM in preparation for its use in sea level rise and climate change impact projections. The model now includes explicit simulation of turbidity, zooplankton, and eelgrass, and performs at a higher skill level for dissolved oxygen (DO) and ocean acidification (OA) or pH predictions. The SSM had previously demonstrated that the effects of the altered ocean chemistry in the upwelled shelf waters as a result of climate change would propagate into the inner Salish Sea and impact biogeochemistry, resulting in higher predicted algal biomass, a potential species shift from diatoms towards dinoflagellates, and increased regions of hypoxia and acidification (Khangaonkar et al. 2019). Since then, to improve ecological response predictions, micro- and meso-zooplankton kinetics have been incorporated, along with eelgrass, which may compete with phytoplankton for available nutrients in the photic zone along the shorelines. Figure 4 provides updated projections for ocean acidification impacts in the Salish Sea for Y2095. Results point to the possibility that the bottom layer of the Salish Sea water column (lower 15% of water depth) will be exposed to low pH waters with $\Omega_A < 1$, 100% of the time. For the bottom layer, which already experiences exposure to

corrosive water in present condition, this represents an increase of approximately 20%. However, for the surface waters including the photic zone, the projection for the future Y2095 scenario represents a near doubling, over a 114% increase in exposure to waters with $\Omega_A < 1$ (Khangaonkar et al. 2021; Note: these results are limited in that they are based on projections from a single ensemble member run of the National Center for Atmospheric research (NCAR) Community Earth System Model (CESM) and must be interpreted with appropriate caution. However, we believe that the results still provide a useful peek into the type of response one may expect over the Salish Sea in the future.)

In collaboration with University of Washington (UW) and Washington State Department of Fish and Wildlife, and with USEPA support, a toxics fate and transport module for SSM is currently under development. The SSM-toxics module development effort targets tracking of PCBs and metals from sources such as outfalls through the water column, to produced organic particles, and through the food chain to fish tissue data that has been collected by the Washington Department of Fish and Wildlife over many years. The model was also used by the same team in connection with tracking of toxics in Puget Sound, which includes pharmaceuticals such

as opioids and the chemotherapy drug melphalan, along with a suite of 62 other contaminants (James et al. 2020). The SSM was used to compute a Salish Sea-wide map of effluent concentration from 99 wastewater outfalls over a one-year period to examine cumulative effects. An outfall effluent plume module FVCOM-Plume has been developed to provide dynamic plume dilution and transport analysis in tidal environments (Premathilake & Khangaonkar 2019). We expect that dynamic application of SSM with FVCOM-Plume will help regulatory agencies with accurate aquatic and human health exposure assessments in the Salish Sea.

In collaboration with NOAA Center for Operational Oceanographic Products and Services (COOPS), Ecology, UW-NANOOS, the PNNL SSM team is developing a high-resolution version of SSM towards SSM-OFS, an Operational Forecast System for the Salish Sea, for navigation and maritime emergency response support. Community access to SSM is available through the Salish Sea Modeling Center that was recently established through a memorandum of understanding between University of Washington, Tacoma and PNNL with support from USEPA, Puget Sound Partnership, City of Tacoma, and the University of Washington.

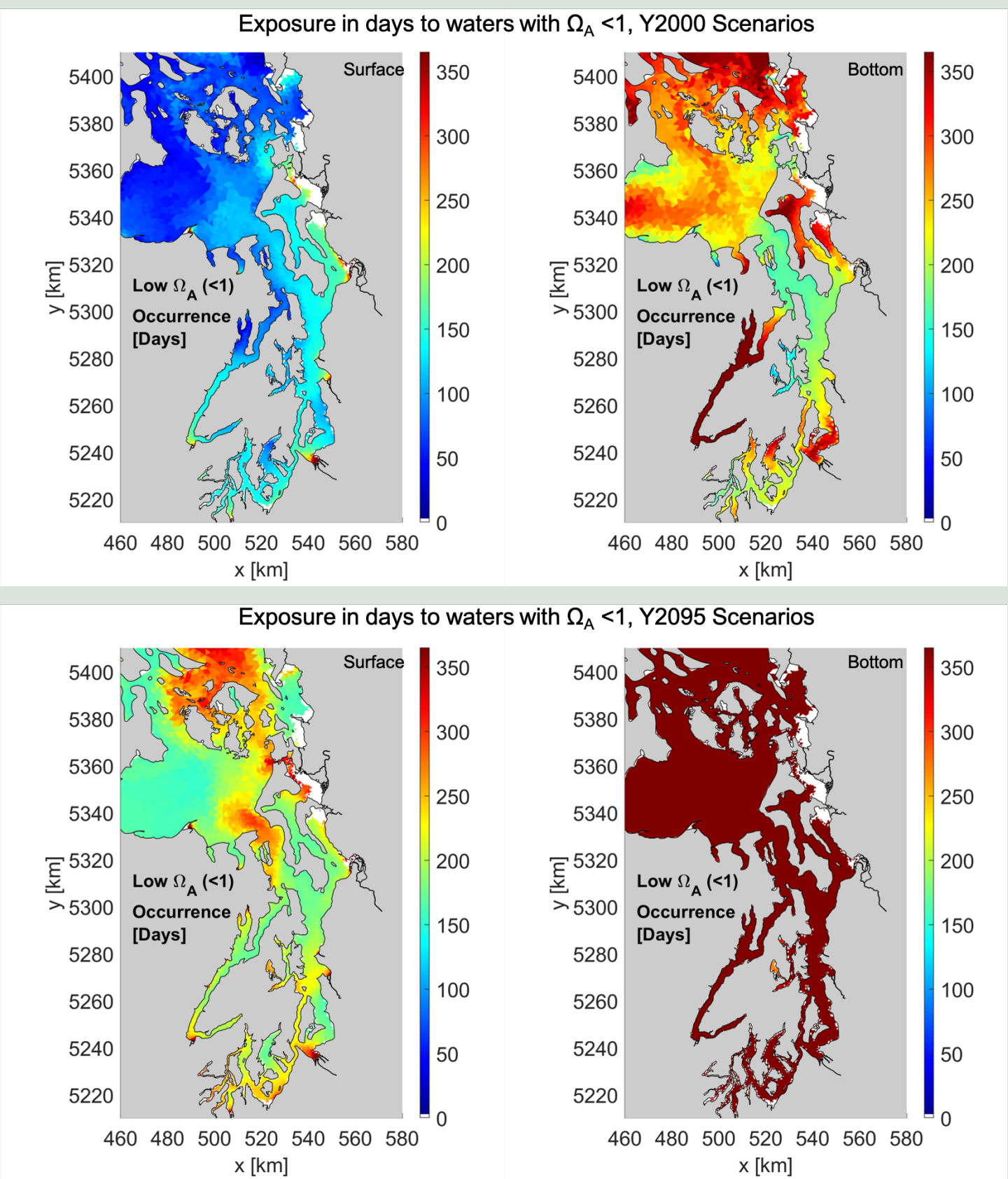


Figure 4. Projected exposure in days to waters corrosive to shell forming organisms with aragonite saturation $\Omega_A < 1$ for surface and bottom layers of Salish Sea. Top panel: Historical Y2000 scenario simulation, surface and bottom layer. Bottom panel: Future Y2095 simulation, surface and bottom layer. Surface layer corresponds to upper 3% of the water column and bottom layer corresponds to lower 15% of the water column.

14 | EELGRASS WASTING DISEASE

Olivia Graham, Morgan Eisenlord, and Dr. Drew Harvell, Department of Ecology and Evolutionary Biology, Cornell University

Rising seawater temperatures can increase the risk of disease outbreaks in many taxa (Burge et al. 2014; Maynard et al. 2016; Burge & Hershberger 2020). In addition, heat waves, which occur when seawater temperature exceeds a threshold, are increasing in severity, duration, and intensity (Hobday et al. 2016; Oliver et al. 2018) and have been associated with numerous ecological changes in our waters. For example, documented impacts from the longest heat wave described to date, which occurred in the Northeast Pacific Ocean from 2014 to 2016, include mass mortality events of planktivorous seabirds, widespread harmful algal blooms, ecosystem regime shifts from bull kelp forests to sea urchin barrens, massive shifts in plankton productivity and composition, and an outbreak of seastar wasting disease in numerous species including the sunflower star (*Pycnopodia helianthoides*), a pivotal predator (Cavole et al. 2016; Gentemann et al. 2017; Harvell et al. 2019; Rogers-Bennett & Catton 2019).

Pathogens are potentially the ultimate keystone species in that their small biomass can have massive impacts that ripple through ecosystems. However, the triggers to epidemics are likely multivariate and complex, involving a combination of host stress, environmental conditions, and changes in biological communities. Progress in understanding the conditions that lead to epidemics has been hindered by a lack of integration among these various components that determine susceptibility and resilience to pathogens. Disease outbreaks can be particularly damaging when they affect ecosystem engineers, such as corals and seagrasses (Burge et al. 2014; Harvell & Lamb 2020). Outbreaks of wasting disease in seagrasses are one of a myriad of

stressors associated with declining temperate and tropical seagrass meadows around the globe (Short et al. 1988; Waycott et al. 2009; Sullivan et al. 2013; Martin et al. 2016; Sullivan et al. 2018). The largest outbreak of wasting disease occurred in the 1930s along the European and American coastlines of the Atlantic Ocean (Renn 1936; Godet et al. 2008). During this outbreak, eelgrass meadows suffered up to 90% mortality. Impacts of the outbreak include altered sediment distribution and disrupted coastal food chains, fisheries, and migratory waterfowl (Short et al. 1988). These examples demonstrate the cascading ecological impacts of infectious diseases in foundation species (Hughes et al. 2008; Waycott et al. 2009; Plummer et al. 2013).

In recent years, eelgrass in critical estuaries on both the United States Atlantic and Pacific coasts has declined. Eelgrass meadows are affected globally by a wasting disease caused by the protozoan *Labyrinthula zosterae*. There are other disease agents under investigation that can also damage eelgrass, but wasting disease caused by *L. zosterae* is currently the most damaging in our waters.

Levels of eelgrass wasting disease are high in the San Juan Islands (Groner et al. 2016) and Puget Sound. Intertidal and subtidal seagrass wasting disease prevalence and severity were extremely high at field sites in the San Juan Islands (North Cove, Beach Haven, Indian Cove, False Bay, and 4th of July) and Puget Sound (Clinton-Whidbey, Big Gulch, Carkeek, Clearwater Casino, and Shingle Mill) in 2017 and 2018 (and ongoing). Prevalence exceeded 50% at all intertidal sites in both years and was higher in most intertidal than subtidal sites. Severity of infections

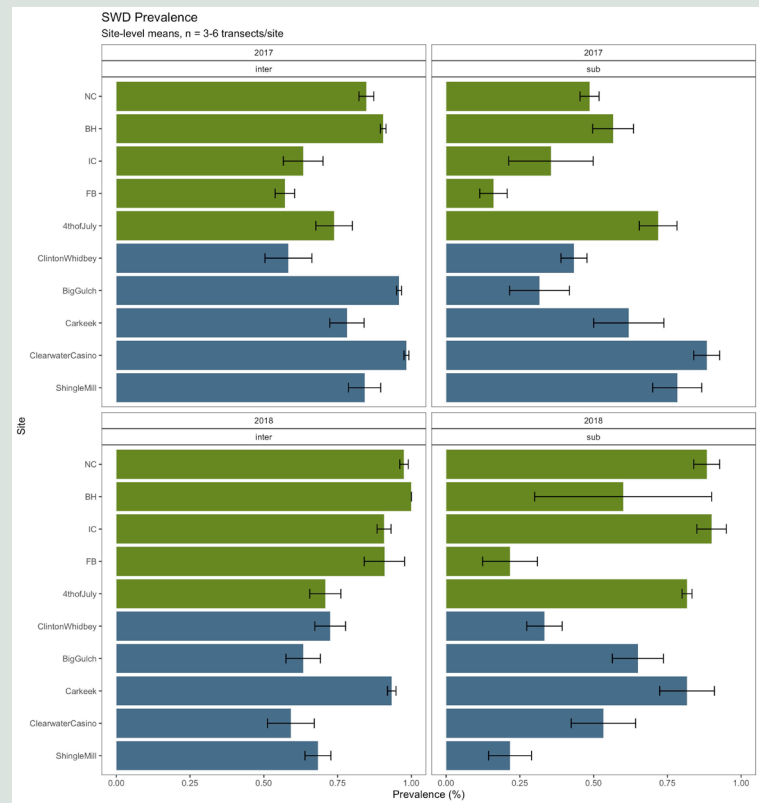
were higher in intertidal than subtidal sites in the San Juan Islands and more variable in Puget Sound.

Our time-series studies from 2012 to 2017 (and ongoing) show sharply increasing levels of disease correlated with warming winter and spring temperatures (Groner et al. under review).

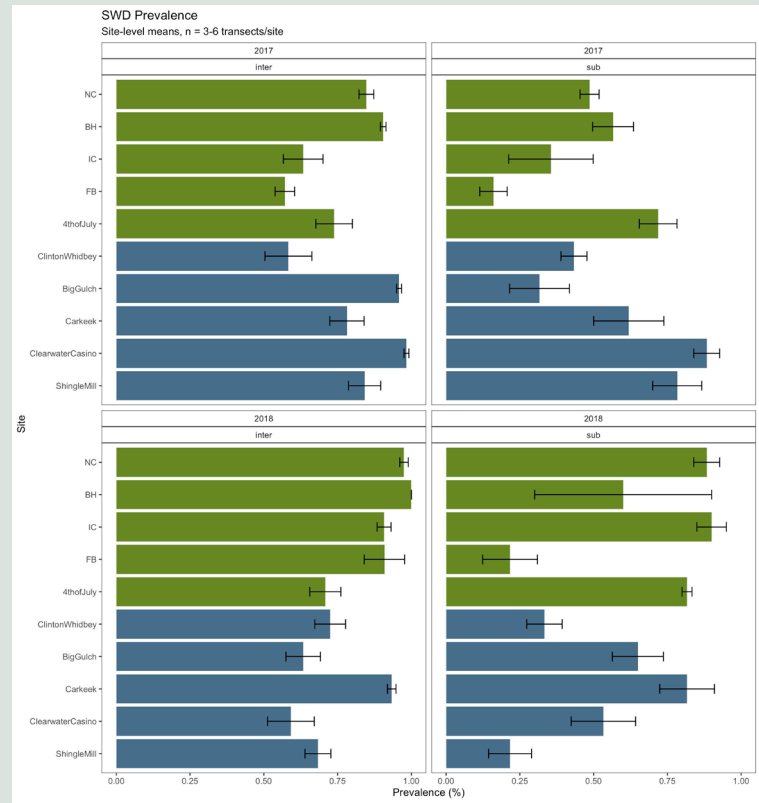
These increasing levels of disease are a threat to sustainability of eelgrass meadows, our most valuable marine habitat, vital for fish development and filtration services and blue carbon mitigation.



Shallow intertidal eelgrass with bubble snail eggs at False Bay, San Juan Island, WA. Photo credit: Sarah Petrini.



Prevalence (proportion of diseased blades, n = 40/transect, 3 transects per site) of disease in intertidal and subtidal eelgrass meadows in the San Juan Islands and Puget Sound.



Severity (percent of a blade damaged by lesions) of disease in the San Juan Islands and Puget Sound eelgrass meadows.

Dr. Ronald Thom, Staff Scientist Emeritus, Pacific Northwest National Laboratory

In the summer of 1991, out of curiosity and to train interns in measuring the fundamental ecological process of primary production, we started measuring the growth rate of eelgrass (*Zostera marina*) every two weeks in a lush meadow near our lab at the mouth of Sequim Bay. In all but two summers since then, with the help of student interns and volunteers, we have continued to measure the growth rate between May and August. After about ten years, we started to look at the data. Although visually we did not see obvious differences in the meadow, we found that the growth rates varied substantially between summers. We wondered why.

In an effort to explain the results, we first organized the knowledge on the factors that affect eelgrass. It is well established that eelgrass is found at the dynamic interface between the lower intertidal and the shallow subtidal zones where suitable conditions of the sediment, wave energy, salinity, temperature, and light occur. The fact that eelgrass does not like to dry out (desiccate) limits its upper extent in the intertidal zone. Because it needs light to live and grow, and because light decreases in water with depth as well as turbidity, the lower depth it can exist at is a function of the amount of light reaching the bottom. So that explains the broad range of distribution, but does it help explain why eelgrass grew faster some years than others in our study plot? We enhanced our monitoring of growth by including light and temperature measurements, and collected data throughout Puget Sound on depth distribution of eelgrass. We also examined the data developed by the Washington State Department of Natural Resources eelgrass monitoring program, which began in the early 2000s and engaged eelgrass experts in discussions about our question.

During the 1990s, the issue of sea level rise (SLR) driven by global warming began to be studied more closely. We had an early interest in the effect of SLR on tidal marshes and studied accretion rates of marshes in our region in 1991. Sea level obviously could affect eelgrass also. The SLR scenarios under investigation were largely steady increases in sea level, with nuances associated with local conditions such as land subsidence and isostatic rebound. Based on the studies by the Washington State Department of Ecology and others, it turned out that the relative SLR rate on the shoreline in the Sequim Bay area was close to zero; there was no effect on eelgrass based on this scenario. However, while exploring the sea level variation tracked by NOAA, we noticed that the tide level recorded by sensors in Port Angeles and Port Townsend varied from the tide level predicted by tide models on many days. Short-term variations appeared to be caused by localized storm events pushing water levels higher via storm surge. We also noticed that longer-term (i.e., weeks to months) differences in mean sea level were occurring. We termed these longer-term variations mean sea level anomalies.

Several conditions can cause anomalies in mean sea level, among them being local storms and El Nino and La Nina events. El Nino events result in heating and thermal expansion of the North Pacific Ocean. The Oceanic Nino Index (ONI) is basically the temperature of the surface water in a region near the equator compared with the long-term mean. An ONI between -0.5 and +0.5 indicates a neutral ONI. Values of the ONI above and below that range indicate El Nino and La Nina conditions, respectively. The monthly mean sea level anomalies recorded near Sequim Bay between 1990 and 2013 ranged from -0.16 to +0.38 meters—a total range of 0.54 meters or almost 2 feet.

This longer-term variation could influence eelgrass growth by sustained periods of either low water levels or high water levels. Knowing the factors that control eelgrass growth, higher tides could enhance growth of the plants at our intertidal site by reducing the period of drying during summer, whereas extended lower tides could slow growth via greater desiccation. Plotting the growth rates over a period of 1991 to 2013 against mean sea level and the ONI showed a reasonably consistent pattern, with higher growth rates during periods of higher mean sea level, especially during El Niños and vice versa with La Ninas. Also, plotting growth rates against desiccation stress (measured in percent of daytime hours the plants were emerged) as well as the mean maximum temperature showed strong negative correlations with growth.

So we think we have at least part of a plausible explanation for the variation in growth rate. We examined old long-term data on eelgrass shoot density from Willapa Bay and near the Clinton Ferry Terminal on Whidbey Island and found that the variation seen there could be at least partially explained by sea level and/or temperature variations. In a study of Padilla Bay, Kairis and Rybczyk (2010) found that the steady increase in sea level would result in an increase in eelgrass area. This is because as the sea rises, the area above the current limit of eelgrass would be subjected to less desiccation stress and should be suitable for eelgrass. At the lower depth distribution of eelgrass, the typically clear water should allow eelgrass to persist (not decline), at least until depths and/or turbidity increase substantially.

The portion of the eelgrass meadow where our long-term growth studies were conducted inexplicably started to become less dense in 2014 and finally disappeared in 2016. This collapse of approximately 700m² corresponded with the anomalous warm water conditions termed the Blob. Although we are still trying to figure out the mechanism for this collapse, our observations indicated that Canada geese had started to congregate during this period in numbers we had never seen before. They tended to congregate in the area of our sampling plot, where they were observed eating eelgrass. Unlike Brant geese that only eat the leaves, Canada geese pull

up the leaves and the rhizome. Importantly, eelgrass regenerates its shoots from the rhizome, and with that gone, the eelgrass cannot quickly recover. We are not sure if the geese were the primary cause of the collapse or why they suddenly started to show up on the site, but they surely contributed to it.

Although the collapse necessitated that we relocate our monitoring plot, perhaps one of the things we learned that can be applicable elsewhere is the advantage of monitoring something for a long time (28 years so far) in the same place as where factors influencing variation can be studied. We had the advantage of using a site located within 150 meters of the laboratory to conduct these studies. It has allowed us to tease out causal factors causing eelgrass variation and collapse, and to link these to events occurring hundreds to thousands of miles from the site. Coupling these local long-term findings with research and monitoring done in Salish Sea and globally will help us better understand the longer-term effects of global warming and perhaps other human and natural-derived pressures on coastal ecosystems, and provide clues on how to make these system more resilient to these pressures.

VULNERABILITY ASSESSMENT AND CLIMATE CHANGE ADAPTATION PREPARATION

Excerpted from State of Our Watersheds 2020, authored by the Northwest Indian Fisheries Commission and the Jamestown S’Klallam Tribe

The Jamestown S’Klallam Tribe is on the forefront of addressing tribal vulnerabilities and preparing for climate change. The 2013 Jamestown Climate Vulnerability Assessment and Adaptation Plan provides an assessment of vulnerabilities of tribal resources to the negative impacts of climate change. The plan also identifies adaptation measures that the tribe is working to complete. Sea level rise, ocean acidification and climate models show potential for increased risks to critical habitats, tribal infrastructure and tribal health.

As one of the first tribes in western Washington to complete a climate adaptation plan and vulnerability assessment, the Jamestown S’Klallam Tribe has identified and prioritized areas where the changing climate conditions (i.e., changing precipitation patterns, sea level rise, ocean acidification) will leave tribal resources, infrastructure, economy and health most vulnerable (Adaptation International 2013). Climate vulnerability depends largely on climate exposure, sensitivity and adaptive capacity (Adaptation International 2013).

The tribe identified many vulnerabilities:

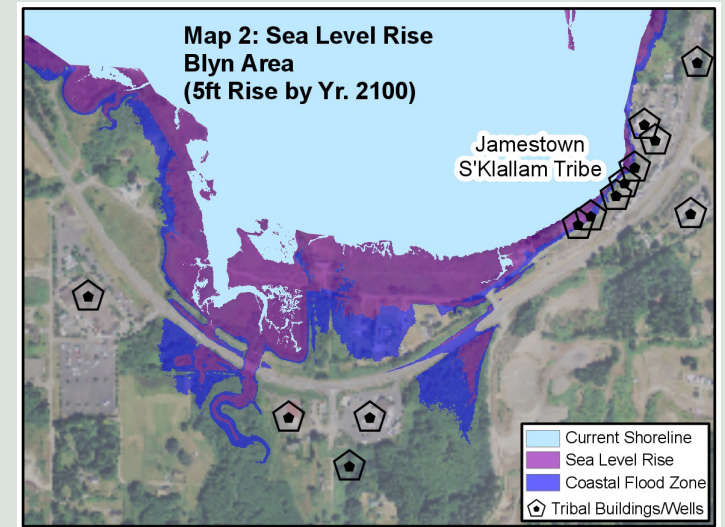
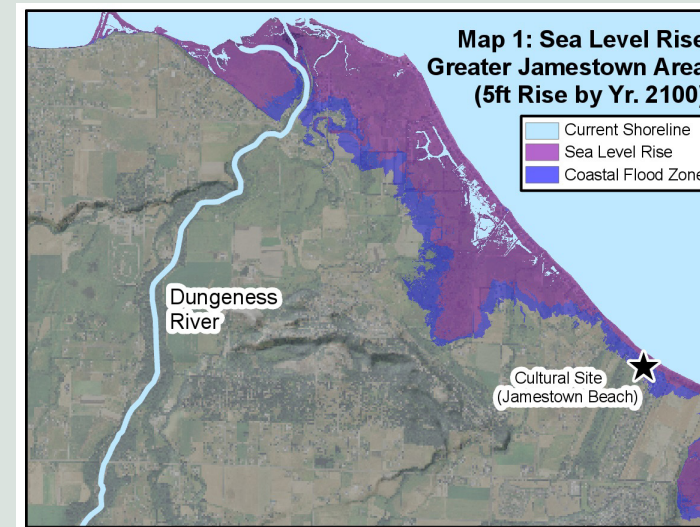
Impact to Salmon which is the foundation for almost all aspects of tribal cultural life and also serve as economic and nutritional resources for the tribe. Salmon will be impacted by the change in timing and amount of winter rains and flooding, scouring of egg redds (nests) during high flows, thermal stress from higher water temperature, and less water availability in the summer.

Oysters and clams also are highly vulnerable under expected conditions. Projected impacts include higher water temperatures and ocean acidification. There will also be an increased occurrence of shellfish poisoning associated with harmful algal blooms (which warmer conditions may favor), diminished health and wellness, economic loss, and increased flooding of tribal buildings, sacred historical places and infrastructure (Adaptation International 2013).

Traditional ways of life and health are extremely vulnerable. The loss or displacement of traditional plants necessary for food and fibers needed for traditional practices is likely. There are potential impacts to Indian health from forest fire smoke and loss of important traditional agricultural food and natural resources.

To ensure continued economic growth, promote long-term community vitality, and protect sensitive resources and assets, it is essential that we incorporate climate change preparedness into our planning efforts and operations.

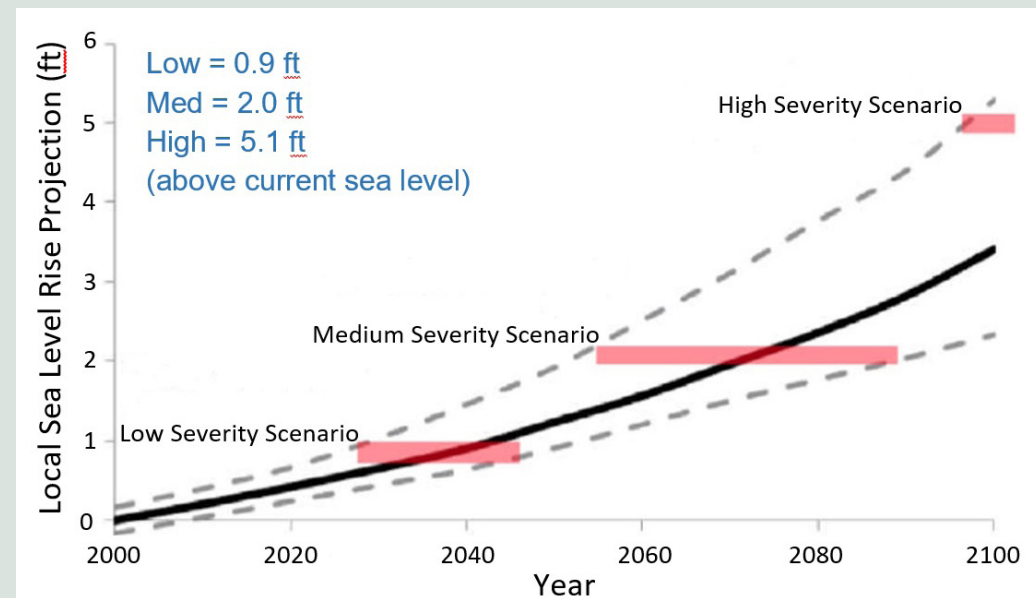
W. Ron Allen
Jamestown S’Klallam Tribe Chairman



Maps 1 and 2. The maps show flood conditions with a sea level rise model under the high severity scenario (Map 1). They show the potential inundation of a vital water source, closed roads, an important cultural site at Jamestown Beach (Map 1), and buildings on the tribal campus in Blyn (Map 2) where flood risk is projected to increase by the end of the century. Map data sources: Adaptation International (2013), National Agriculture Imagery Program (2013). Source: Washington State Department of Ecology Regions (2011) and United States Geological Survey (2019)



Ocean acidification (decrease in ocean pH) will cause waters to become “corrosive to shell-forming organisms such as oyster larvae, clams, mussels and crabs,” posing serious threats to the shellfish in the Strait of Juan de Fuca (Adaptation International 2013). Pictured are the pteropod shells dissolving because of the decreasing ocean pH. Source: Washington State Department of Ecology (2012)



Sea level rise in three scenarios (low, medium, high). This graph is from page 16 of the Jamestown Climate Vulnerability Assessment and Adaptation Plan (Adaptation International 2013). The tribe has identified areas most susceptible to rising sea levels. The assessment has helped the tribe relocate several storage buildings that would have been otherwise affected.

17 | SALISH SEA JELLYFISH

Dr. Correigh Greene, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration

The Salish Sea is home to a diverse community of gelatinous zooplankton (or “jellies”) composed primarily of species from the phyla *Cnidaria* and *Ctenophora*. These include conspicuous large scyphozoan medusa such as lion’s mane (*Cyanea capillata*) and egg-yolk jellies (*Phacellophora camtschatica*), to smaller hydrozoans such as crystal jellies (*Aequorea* spp.) and ctenophores (e.g., *Pleurobrachia* spp.). One abundant species is the moon jelly (*Aurelia labiata*), which forms huge aggregations (or “smacks”) easily observable from the air as well as in the water (Figures 1 and 2; see Eyes Over Puget Sound, Schaub et al. 2018).



Figure 1. *Aurelia* smacks (left) seen from the air and on the water in South Puget Sound from the Eyes Over Puget Sound program. Source: Christopher Krembs, Washington Department of Ecology.



Figure 2. Underwater view of *Aurelia* in a smack. Mature adults are typically 10-30 cm diameter and have been found in densities >170 m⁻³. Source: C. Greene, Unpublished data.



Around the world, scientists have observed increases in the abundance of jellies over the last 50 years. These patterns have been associated with eutrophication, intensive fishing, and changing climate (Purcell et al. 2007), although other research has pointed to large-scale climate variation driving jellyfish blooms (Purcell 2012; Condon et al. 2013; Greene et al. 2015). Are similar changes occurring in the Salish Sea? Are these changes having large impacts to the ecosystem?

These questions have been difficult to address, in part because of a lack of consistent monitoring. Jellies are often ignored as uninteresting bycatch in monitoring studies of pelagic fishes, although interest has recently grown in part due to large blooms recently observed in the northern California Current (Ruzicka et al. 2016). Data synthesized from historical and recent surface trawl data in two sub-basins of Puget Sound indicate that jellyfish catches may have increased since the 1970s (Greene et al. 2015; Figure 3).

While these patterns may appear ominous, they may also reflect natural annual variation (e.g., anomalously high abundances could have occurred in 2003 and 2011), and continuous monitoring can better address long-term changes in biomass. Figure 4 summarizes the only continuous time-series of jellies in the Salish Sea (Greene & Munsch

2020), based on annual surface trawling in Skagit Bay (Northern Puget Sound). Estimates of total jelly biomass per tow illustrate that substantial annual variation exists. High biomass was observed during the marine heatwave of 2015–2016. In subsequent years, however, biomass declined to the second lowest level observed since recording started in 2003, and has subsequently remained below average through 2019. This occurred despite above-average water temperatures in 2019, indicating that water temperatures are not the sole predictor of blooms. Furthermore, individual species appear to respond differently to warming. As exemplified in the lower panel of Figure 4 by the two largest species, the egg yolk jelly and the lion’s mane jelly exhibited strikingly opposite patterns during the 2014-2016 marine heatwave period. Occurrence of both large species was low in the last three years, when smaller jellyfish dominated the biomass. Collectively, these results suggest that the jellyfish community is sensitive to climate signals such as marine water temperatures, although jellyfish do not appear to be systematically increasing in abundance over time.

Whether jellies are on the rise or are episodic in the Salish Sea, the question of their role(s) in the pelagic ecosystem remains an important one with respect to managed species such as Pacific salmon. In this

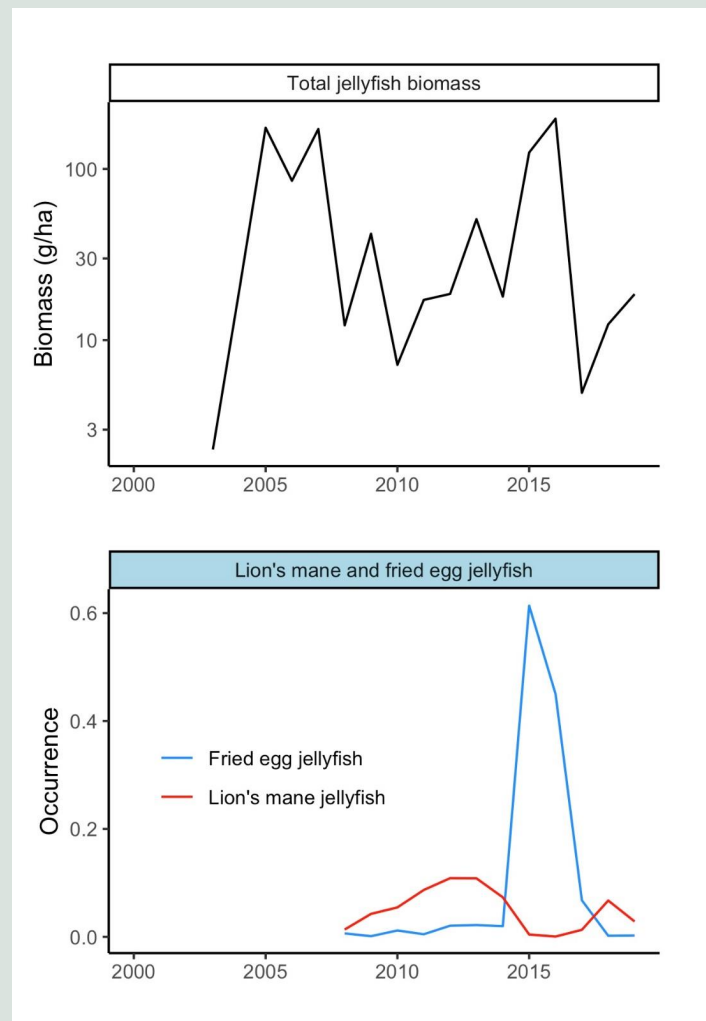


Figure 3. Annual trends in A. total jelly biomass (average g/ha on a logarithmic axis, top panel) or B. occurrence (probability of presence, bottom panel) of lion's mane (red line) and fried egg (blue line) jellies from surface trawls in Skagit Bay. Predicted trends account for seasonal variability, spatial autocorrelation, and water volume swept through net tows. Source: C. Greene, unpublished data.

medusae may preferentially select copepods and fish eggs (Pereira et al. 2014) and also can prey on ichthyoplankton (Bailey & Batty 1983; Figure 5 upper panel), simultaneously serving as competitors and predators of fish.

Aurelia also have the potential to increase primary production by removing zooplankton grazers (Figure 5, middle panel). The increase in turbidity commonly associated with eutrophication gives an advantage to non-visual predators such as *Aurelia* (Purcell 2012), particularly when feeding on prey with good visual acuity, such as fish larvae. Hence, *Aurelia* may impact forage fish, Pacific salmon, and pelagic early life stages of demersal fish species via both direct and indirect pathways through predation and competition, respectively. Note that changing turbidity levels might also provide benefits to fishes from visually orienting predators such as birds and pinnipeds.

Large aggregations of *Aurelia* may also affect water chemistry and nutrient levels through their metabolism, and through decomposition after death. Through their metabolism, aggregations may reduce dissolved oxygen, increase ammonium levels, and allow phytoplankton to proliferate. Hence, *Aurelia* may facilitate bacterial production (Figure 5, bottom panel) that promote eutrophic conditions, to which jellyfish are relatively insensitive compared to fish species (Richardson et al. 2009). Because *Aurelia* has few natural predators, jellyfish medusae may accumulate biomass and in death transfer pelagic carbon to the benthos, acting as trophic "dead ends" and fueling benthic detritivores (Richardson et al.

respect, one of the key species may be the moon jelly, whose huge aggregations can occupy large portions of inlets in the Salish Sea. Species of the genus *Aurelia* are found worldwide and are among those that commonly form huge, nuisance blooms. *Aurelia* have been reported to clog fishing nets and power plant intakes, deter tourism, and interfere with aquaculture (Purcell et al. 2007), all leading to significant regional economic losses. *Aurelia* are also indicators of degraded ecosystem health, often associated with eutrophic habitats, and sometimes low oxygen conditions (Arai 2001).

Aurelia entrain their prey through fluid motions created during swimming, the relative velocity of which, compared to the escape response of their prey, primarily determines prey selection (Costello & Colin 1994). In one study, *Aurelia* shifted their diets from primarily small jellyfish to include more copepods as they grew (Sullivan et al. 1994, Suchman et al. 2008). Mid- to large-size

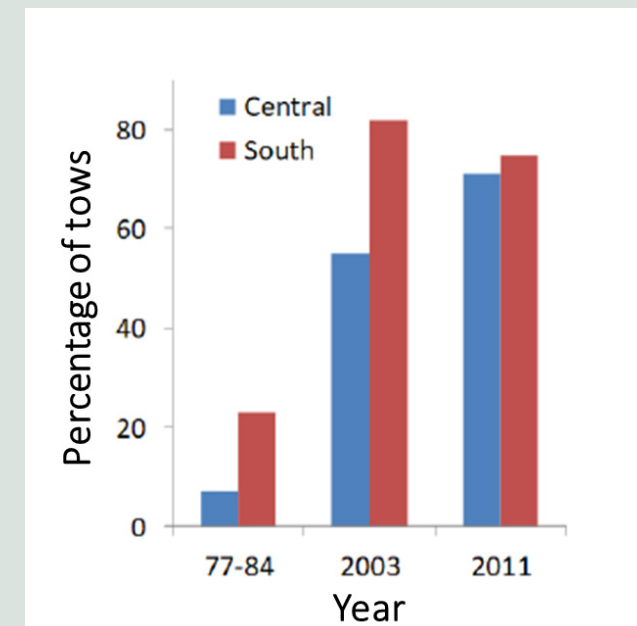


Figure 4. Percent of surface trawl sets in which jellyfish were >75% of the catch biomass in Central and South basins of Puget Sound in 1977-1984, 2003, and 2011. Source: Data from Greene et al. (2015).

2009). Alternately, proliferation of pelagic jellyfish parasites such as hyperiid amphipods may result in retention of carbon biomass within pelagic ecosystems (Hamilton 2016) as they are consumed by fishes (Riascos et al. 2012; Weil et al. 2019).

In sum, multiple pathways may link jellies to components of the Salish Sea's food web that are more important to people. As we learn more about these trophic linkages through ongoing experimental and field research, we are also improving our ecosystem models, which will allow us to put jellies in the context of species like Pacific salmon, geoducks, and rockfish. Combined with better monitoring of distribution and abundance (Eyes Over Puget Sound; Schaub et al. 2018), these models will allow us to examine cascading effects of jellies in the ecosystem and to test scenarios like increasing long-term trends or episodic changes in jelly abundance. Within the next few years, we may have a much better perspective on the roles jellies play (and have played) on the Salish Sea's pelagic ecosystem as these ongoing studies develop.

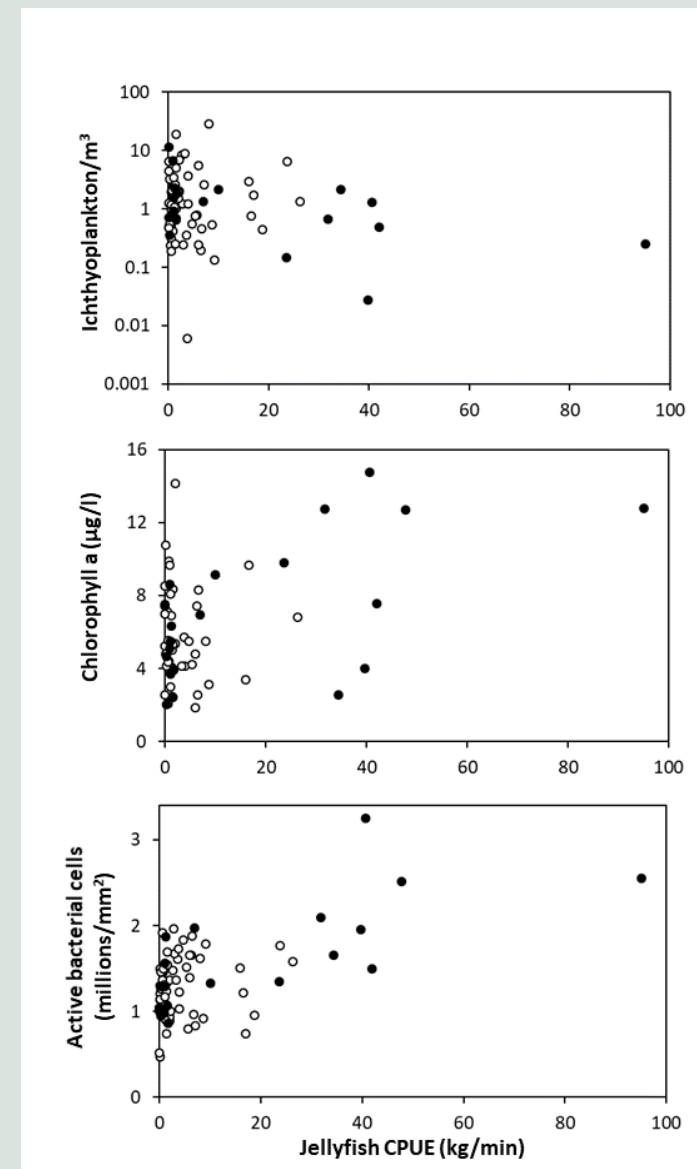


Figure 5. Relationships between ichthyoplankton density, chlorophyll concentration, and metabolically active bacteria as functions of total jellyfish catch per unit effort (CPUE) sampled at 85 sites across Puget Sound in 2011. Filled circles are large embayments, where *Aurelia* aggregations tend to occur within Puget Sound. All measurements of total jellyfish CPUE surpassing 35 kg/min were dominated by *Aurelia* biomass; hence those sites were sampled in the vicinity of *Aurelia* aggregations. Source: C. Greene, Unpublished data.